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ANALYZING CHANGES IN MACRO-LEVEL DRIVERS OF COUNTRY-SPECIFIC EMISSIONS

THE ROLE OF CONSUMPTION, TECHNOLOGY AND TRADE

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ACADEMIC DISSERTATION IN ENVIRONMENTAL CHANGE AND POLICY

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PREFACE AND ACKNOWLEDGEMENTS

It was when I started working with my master's thesis in 2003 I got interested in industrial ecology and science in general. It was all very new to me and I got fascinated by closing the cycles of materials and evaluating the great drivers behind environmental emissions. I had so good time writing my thesis that I stayed at the Department of Environmental Science and Policy and continued with a scientific article. At the time of graduation in 2005, I explored life outside of Helsinki (and science), but eventually, in the beginning of 2007, ended up back to the University. I am grateful to all the organizations that have funded my research along the way. This work has been for the most part funded by the Academy of Finland consortium Indicator Framework for Eco-Efficiency, led by Dr. Jouni Korhonen. Funding was also provided from the Ministry of the Environment, Helsinki Centre for Environment HENVI, Academy of Finland projects AESOPUS and Boomerang, and Fortum foundation. I kindly thank the funding organizations for their respective contributions.

I show my greatest gratitude towards my supervisor, Professor in Environmental Sciences, Pekka Kauppi. I want to thank Pekka for his guidance, support and motivation in all the phases of my thesis. In addition, I wish to thank the pre-examiners of my thesis, Mikael Hildén and Jarmo Vehmas for their dedication and their thorough comments on my thesis. The work improved much thanks to their input.

I also thank the co-authors of my thesis. Riina Antikainen was the supervisor of my master's thesis. She gave me a thorough guidance to Industrial Ecology but also introduced me in to the world of making science. Aapo Rautiainen was of great help in co-authoring the second paper and also helping me with the numbers when needed. I would like to thank Eero Asmala for a great partnership in writing a paper together, sharing fresh ideas and the cozy office. Eero showed his support in the crucial phases of the theses, always spreading positive energy around. Besides, I wish to thank my PhD colleague Laura Sokka and Dr. Pete Tapio, who gave me valuable comments in the final phases of my thesis.

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I thank my colleague students in Environmental Sciences, especially Kaarina and Lotta, for encouragement and for sharing thoughts about science and environment. I also wish to thank all the great people in the Post-graduate School of Industrial Ecology. In addition, I wish to thank all of my lovely friends for just being there and providing me a life outside of science. I thank my family and relatives, especially my parents for the overwhelming support during all these years. Finally, I would like to thank my dear Sampo for being my inspiring co-author, my critical voice in science, and simply, just for being the joy of my life.

LIST OF ORIGINAL PUBLICATIONS AND AUTHORS' CONTRIBUTION

I **Saikku, L.**, Antikainen, R. & Kauppi, P. 2007. Nitrogen and phosphorus in the Finnish energy system, 1900–2003, *Journal of Industrial Ecology* 11 (1), 103–119. © Yale University.

II **Saikku, L.,** Rautiainen, A. & Kauppi, P.E. 2008. The sustainability challenge of meeting carbon dioxide targets in Europe by 2020. *Energy Policy* 36 (2), 730–742. © Elsevier.

III **Saikku, L**. & Asmala, E. 2010. Eutrophication in the Baltic Sea: The role of salmonid aquaculture, consumption and international trade. *Journal of Industrial ecology, in press.* © Yale University.

IV **Saikku, L.** & Soimakallio, S. 2008. Top-down approaches for sharing GHG emission reductions - Uncertainties and sensitivities in the 27 European Union Member States. *Environmental Science & Policy* 11 (8), 723–734. © Elsevier.

In paper I, the ImPACT analysis was performed by Laura Saikku. The SFA data were jointly collected and analysed by Laura Saikku and Riina Antikainen. Pekka Kauppi commented on the paper.

In paper II, the historical data were collected and analysed by Aapo Rautianen and Laura Saikku. The scenario analysis was performed by Aapo Rautiainen. The manuscript was co-written by Laura Saikku and Aapo Rautiainen. Pekka Kauppi also co-wrote and commented on the paper.

In paper III, the data were jointly collected, and were analysed by Laura Saikku. The manuscript was co-written by Laura Saikku and Eero Asmala.

In paper IV, the data were jointly collected and analysed and the manuscript co-written by Laura Saikku and Sampo Soimakallio.

ABSTRACT

Industrial ecology is an important field of sustainability science. It can be applied to study environmental problems in a policy relevant manner. Industrial ecology uses ecosystem analogy; it aims at closing the loop of materials and substances and at the same time reducing resource consumption and environmental emissions. Emissions from human activities are related to human interference in material cycles. Carbon (C), nitrogen (N) and phosphorus (P) are essential elements for all living organisms, but in excess have negative environmental impacts, such as climate change (CO_2, CH_4 N_2O), acidification (NO_x) and eutrophication (N, P).

Several indirect macro-level drivers affect emissions change. Population and affluence (GDP/capita) often act as upward drivers for emissions. Technology, as emissions per service used, and consumption, as economic intensity of use, may act as drivers resulting in a reduction in emissions. In addition, the development of country-specific emissions is affected by international trade.

The aim of this study was to analyse changes in emissions as affected by macro-level drivers in different European case studies. ImPACT decomposition analysis (IPAT identity) was applied as a method in papers I–III. The macro-level perspective was applied to evaluate CO_2 emission reduction targets (paper II) and the sharing of greenhouse gas emission reduction targets (paper IV) in the European Union (EU27) up to the year 2020. Data for the study were mainly gathered from official statistics. In all cases, the results were discussed from an environmental policy perspective.

The development of nitrogen oxide (NO_x) emissions was analysed in the Finnish energy sector during a long time period, 1950–2003 (paper I). Finnish emissions of NO_x began to decrease in the 1980s as the progress in technology in terms of NO_x/energy curbed the impact of the growth in affluence and population.

Carbon dioxide (CO_2) emissions related to energy use during 1993–2004 (paper II) were analysed by country and region within the European Union. Considering energy-based CO_2 emissions in the European Union, dematerialization and decarbonisation did occur, but not sufficiently to offset population growth and the rapidly increasing affluence during 1993–2004.

The development of nitrogen and phosphorus load from aquaculture in relation to salmonid consumption in Finland during 1980–2007 was examined, including international trade in the analysis (paper III). A regional environmental issue, eutrophication of the Baltic Sea, and a marginal, yet locally important source of nutrients was used as a case. Nutrient emissions from Finnish aquaculture decreased from the 1990s onwards: although population, affluence and salmonid consumption steadily increased, aquaculture technology improved and the relative share of imported salmonids increased.

According to the sustainability challenge in industrial ecology, the environmental impact of the growing population size and affluence should be compensated by improvements in technology (emissions/service used) and with dematerialisation. In the studied cases, the emission intensity of energy production could be lowered for NO_x by

cleaning the exhaust gases. Reorganization of the structure of energy production as well as technological innovations will be essential in lowering the emissions of both CO_2 and NO_x. Regarding the intensity of energy use, making the combustion of fuels more efficient and reducing energy use are essential. In reducing nutrient emissions from Finnish aquaculture to the Baltic Sea (paper III) through technology, limits of biological and physical properties of cultured fish, among others, will eventually be faced. Regarding consumption, salmonids are preferred to many other protein sources. Regarding trade, increasing the proportion of imports will outsource the impacts.

Besides improving technology and dematerialization, other viewpoints may also be needed. Reducing the total amount of nutrients cycling in energy systems and eventually contributing to NO_x emissions needs to be emphasized. Considering aquaculture emissions, nutrient cycles can be partly closed through using local fish as feed replacing imported feed.

In particular, the reduction of CO_2 emissions in the future is a very challenging task when considering the necessary rates of dematerialisation and decarbonisation (paper II). Climate change mitigation may have to focus on other greenhouse gases than CO_2 and on the potential role of biomass as a carbon sink, among others. The global population is growing and scaling up the environmental impact. Population issues and growing affluence must be considered when discussing emission reductions. Climate policy has only very recently had an influence on emissions, and strong actions are now called for climate change mitigation. Environmental policies in general must cover all the regions related to production and impacts in order to avoid outsourcing of emissions and leakage effects.

The macro-level drivers affecting changes in emissions can be identified with the ImPACT framework. Statistics for generally known macro-indicators are currently relatively well available for different countries, and the method is transparent. In the papers included in this study, a similar method was successfully applied in different types of case studies. Using transparent macro-level figures and a simple top-down approach are also appropriate in evaluating and setting international emission reduction targets, as demonstrated in papers II and IV. The projected rates of population and affluence growth are especially worth consideration in setting targets. However, sensitivities in calculations must be carefully acknowledged. In the basic form of the ImPACT model, the economic intensity of consumption and emission intensity of use are included. In seeking to examine consumption but also international trade in more detail, imports were included in paper III. This example demonstrates well how outsourcing of production influences domestic emissions. Country-specific production-based emissions have often been used in similar decomposition analyses. Nevertheless, trade-related issues must not be ignored.

TIIVISTELMÄ

Kulutuksen, teknologian ja kansainvälisen kaupan vaikutus päästöjen kehitykseen

Teollinen ekologia on merkittävä ympäristötieteen ala, jota voidaan soveltaa päätöksenteon tueksi. Teollisen ekologian perusajatuksena on ottaa mallia luonnosta: sulkea materiaalien ja aineiden kiertoja sekä käyttää energiaa tehokkaasti. Tavoitteena on vähentää luonnonvarojen käyttöä ja päästöjä ympäristöön. Haitalliset päästöt liittyvät usein siihen, että ihminen häiritsee materiaalien kiertojen luonnollista toimintaa. Hiili (C), typpi (N), ja fosfori (P) ovat elintärkeitä alkuaineita kaikille olioille, mutta liian suurina määrinä ja väärässä paikassa ne voivat aiheuttaa haitallisia ympäristövaikutuksia kuten ilmastonmuutosta (CO_2, CH_4 N_2O), happamoitumista (NO_x) ja rehevöitymistä (N, P).

Ympäristömuutosten taustalla on monia epäsuoria makrotason tekijöitä. Väestö ja varallisuus (BKT/hlö) vaikuttavat usein päästöjä kasvattavasti. Palveluiden, kuten energian tai ruoan, käytön päästöintensiivisyys (päästöt/palvelu) sekä talouden materiaali- ja energiaintensiteetti (palvelu/BKT) vaikuttavat myös päästöjen kehitykseen. Lisäksi maakohtaisiin päästöihin vaikuttaa kansainvälinen kauppa.

Tässä tutkimuksessa tarkasteltiin makrotason tekijöiden vaikutusta päästöjen kehittymiseen erilaisten eurooppalaisten tapaustutkimusten avulla. Menetelmänä artikkeleissa I-III käytettiin ImPACT-dekompositioanalyysiä (IPAT-identiteetti). Makrotason näkökulmaa sovellettiin myös hiilidioksidipäästöjen vähennystavoitteiden arviointiin (artikkeli II) ja kasvihuonekaasupäästöjen vähennystavoitteiden jakamiseen (artikkeli IV) Euroopan Unionissa (EU27) vuoteen 2020. Pääasialliset aineistot olivat viralliset tilastot. Kaikissa tapauksissa tuloksia tarkasteltiin ympäristöpoliittisesta näkökulmasta.

Suomen energiantuotannon typen oksidien (NO_x) päästöjen historiallista kehitystä tarkasteltiin pitkältä ajanjaksolta, 1950–2003 (artikkeli I). Suomessa typen oksidien päästöjen kasvu taittui 1980-luvulla. Tuolloin teknologian (NO_x/energia) tehostuminen taittoi väestön ja varallisuuden kasvun vaikutuksen.

Euroopan Unionin hiilidioksidipäästöjen kehitystä tarkasteltiin vuosina 1993–2004 maittain ja koko Euroopan Unionin laajuisesti (artikkeli II). Euroopan Unionin hiilidioksidipäästöt eivät kääntyneet laskuun tarkastellulla ajanjaksolla. Energiantuotannon hiilidioksidi-intensiivisyyden ja talouden energiaintensiteetin pieneneminen eivät taittaneet talouden ja väestön kasvun vaikutusta vuosina 1993–2004.

Menetelmää sovellettiin energiasektorin ohella myös ruoantuotantoon ja -kulutukseen. Suomen kirjolohen kasvatuksen typpi- ja fosforipäästöjä sekä lohenkulutusta tarkasteltiin vuosina 1980–2007 artikkelissa III, jossa kansainvälinen kauppa sisällytettiin analyysiin. Tapauksen avulla käsiteltiin alueellista ympäristöongelmaa, Itämeren rehevöitymistä, ja marginaalista mutta paikallisesti merkittävää päästölähdettä, kalankasvatusta. Suomen kalankasvatuksen ravinnepäästöt alkoivat vähentyä 1990-luvulta: väestö, varallisuus ja lohen kulutus kasvoivat, mutta kalankasvatusteknologia tehostui, ja lohikalan tuonti lisääntyi merkittävästi.

Teollisen ekologian kestävyyshaasteen mukaan väestön ja varallisuuden kasvun aiheuttama päästöjen kasvu tulisi taittaa teknologiaa (päästöt/palvelu) tehostamalla ja talouden materiaali-intensiteettiä pienentämällä eli dematerialisaatiolla. Tutkituissa tapauksissa energiantuotannon NO_x-päästöintensiivisyyttä voi pienentää mm. puhdistamalla typpeä savukaasuista. Energiantuotannon rakennemuutos ja teknologiset innovaatiot ovat olennaisia sekä typen että hiilidioksidin päästöjen pienentämiseen. Talouden energiaintensiteettiä voi pienentää tehostamalla polttoaineiden polttoa ja vähentämällä energian käyttöä. Suomalaisen kalatalouden päästöjen vähentäminen teknologian avulla onnistuu vain tiettyyn rajaan saakka, sillä kasvatuskalan biologisten ja fyysisten ominaisuuksien rajat tulevat lopulta vastaan. Kalankasvatuksen päästöjä on vaikea vähentää lohikalojen kulutusta vähentämällä, sillä lohen kulutus on kasvussa. Kotimaisen kalatalouden päästöjen vähentäminen ulkomaisen lohen tuontia lisäämällä puolestaan siirtää kalankasvatuksen ympäristövaikutukset Suomen ulkopuolelle.

Teknologian tehostamisen ja dematerialisaation ohella päästöjen vähentämiseen tarvitaan todennäköisesti muitakin näkökulmia. Energiajärjestelmässä kiertävien ravinteiden kokonaismäärää vähentämällä voidaan vaikuttaa välillisesti myös päästöjen määrään. Lohenkasvatuksen päästöjen osalta ravinnekiertoja voidaan sulkea osittain korvaamalla kalarehun sisältämä tuontikala kotimaisella kalalla.

Erityisesti hiilidioksidipäästöjen vähentäminen tulevaisuudessa on erittäin haastavaa, ajatellen ilmastotavoitteiden saavuttamiseksi vaadittavaa dematerialisaatiota ja energiantuotannon päästöintensiivisyyden pienentämistä (artikkeli II). Ilmastonmuutoksen hillinnässä muutkin kasvihuonekaasut kuin artikkelissa II tutkittu hiilidioksidi ja metsänielut tulee ottaa huomioon. Myös väestökysymykset ja bruttokansantuotteen kasvu tulee ottaa huomioon, kun tarkastellaan päästöjen vähentämistä. Ilmastopolitiikka on vaikuttanut päästöjen vähentämiseen vasta suhteellisen vähän aikaa, ja nyt tarvitaan nopeita ja tehokkaita toimia ilmastonmuutoksen hillitsemiseksi. Ympäristöpolitiikan tulee olla kattavaa liittyen tuotantoon ja ympäristövaikutuksiin, jotta päästöjen ulkoistaminen ja päästövuodot saadaan estettyä.

ImPACT-dekompositioanalyysi on yksinkertainen ja selkeä menetelmä päästöjen muutosten syiden tarkasteluun makrotasolla. Tilastoja yleisesti tunnetuista makroindikaattoreista on usein hyvin saatavilla. Menetelmä on myös läpinäkyvä. Tämän tutkimuksen artikkeleissa menetelmää sovellettiin erityyppisissä tapaustutkimuksissa. Makro-indikaattorien käyttö soveltuu myös kansainvälisten päästövähennystavoitteiden arvioimiseen ja asettamiseen (artikkelit II, IV). Väestön ja varallisuuden kasvun huomioon ottaminen on erityisen tärkeää asetettaessa kansainvälisiä ympäristötavoitteita. Makrotason tarkastelu on kuitenkin karkea, ja ennustuksiin liittyy paljon epävarmuutta. ImPACT-yhtälön perusmuodossa otetaan huomioon palveluiden kulutuksen taloudellinen intensiteetti ja palveluiden päästöintensiivisyys. Mitä useampaan muuttujaan ImPACT-yhtälö jaetaan, sitä yksityiskohtaisempaa tietoa muutostekijöistä saadaan. Kulutusta ja kansainvälistä kauppaa tutkittiin tarkemmin artikkelissa III, jossa lohen tuonti sisällytettiin tarkasteluun. Esimerkki osoitti hyvin, miten tuotannon ulkoistaminen vaikuttaa kotimaassa syntyviin päästöihin. Kansainvälinen kauppa tulisikin ottaa huomioon vastaavissa analyyseissä.

1 INTRODUCTION

1.1 BACKGROUND

Human activities have changed the environment, most intensively since the industrial revolution, and especially since 1950s when the population of the World still was no larger than 2.8 billion. Emissions from human activities are related to human interference in material cycles. Carbon (C), nitrogen (N) and phosphorus (P) are essential elements for all living organisms, but in excess in the wrong place they have negative environmental impacts, such as climate change (CO_2, CH_4 N_2O), acidification (NO_x) and eutrophication (N, P). Carbon dioxide concentrations in the atmosphere have increased from pre-industrial levels of 280 ppm (Neftel et al. 1994) to 316 ppm in 1960 and 385 ppm in 2008 (Keeling et al. 2009). Fossil emissions of carbon dioxide from fossil-fuel burning, cement manufacture and gas flaring totalled 8 230 million tons of C in 2006, increasing more than ten-fold during a century (Boden et al. 2009). The annual net flux of carbon to the atmosphere from land-use changes has been estimated at 1500 million tons of C during 2003–2005, approximately twice as much as a century ago (Houghton 2008). The amount of reactive nitrogen has doubled due to human activities, mainly due to the combustion of fossil fuels and the use of fertilizers (Vitousek et al. 1997, Galloway et al. 2008, Gruber & Galloway 2008). Mobilization of phosphorus has at least doubled compared to its natural rate (Filipelli 2008, Smil 2000, Liu et al. 2008). This is mainly due to the use of fertilizers, intensified erosion and increased wastewaters.

Human-induced emissions can be studied with the methods and perspective of industrial ecology (Lifset & Graedel 2002). Industrial ecology examines flows of materials and also macro-level drivers of ecosystem change. Macro-level drivers include demographic factors, economic factors such as globalisation and trade, and the socio-political framework with governance and institutions (MEA 2005). Of these, population size, affluence (GDP/capita), the economic intensity of consumption, technology and international trade are examined more closely in this dissertation. Development in these macro-level drivers in relation to changes in emission of carbon, nitrogen and phosphorus are examined in three separate case studies. In addition, macro-level top-down viewpoint is used in scenario analysis.

1.2 CARBON, NITROGEN AND PHOSPHORUS EMISSIONS AFFECT THE ENVIRONMENT

There are three central environmental problems related to human interference with material cycles of carbon, nitrogen and phosphorus. Climate change can be considered as one of the largest environmental problems facing humankind. Climate change is accelerated by the growth in greenhouse gas emissions, mainly CO_2, to the atmosphere. Since pre-industrial times, global temperature has increased by 0.7 °C (IPCC 2007). The global mean temperature is expected to increase significantly and there is a growing risk of extreme climatic events, such as changes in precipitation, sea level rise and the threat of abrupt climate change, and furthermore a risk of catastrophic events (IPCC 2007). To limit the possibility of extreme climate events, the rise in the global average temperature should be limited to 2 °C above the pre-industrial level. Global greenhouse gas emissions amounted to 41 755 Mt CO_2 eq in 2000 (Baumert et al. 2005). The US, China, the EU, Russia, India and Japan are the largest emitters of the world. Carbon dioxide, the most important human-induced greenhouse gas (77% share), mainly originates from the combustion of fossil fuels (70%) and due to land-use changes (25%) (Baumert et al. 2005, data for 2000). Methane (CH_4) and nitrous oxide (N_2O) emissions, mainly derived from food production (15% of total GHG emissions) and waste management (<5% of total emissions), are also significant.

The ecosystems most sensitive to acidification are nutrient-poor lakes and forests, especially those in northern Europe. Acidification occurs when the capacity of the soil or water bodies to neutralise acidifying atmospheric deposition declines. In more fertile regions, soils and the bedrock typically contain higher concentrations of calcium, which helps to prevent acidification. Acidification prevents trees from growing, erodes buildings and contributes to lung and heart diseases. In the 1960s and 1970s, long-range acid deposition resulted in thousands of lakes becoming too acidic for many fish species to survive. During the 1980s, also large areas of forests in central Europe were exposed to acid rain (EEA 2005). The combustion of fossil fuels in energy production, in addition to traffic, produces emissions of nitrogen oxides. Sulphur emissions also contribute to acidification. In the European Union, emissions of nitrogen oxides declined by 37% over the period 1990-2007. In Finland, NO_x emissions have been around 25–35% lower in the 2000s than in 1990. However, sulphur emissions have decreased even more and the role of NO_x emissions has become dominant. The NO_x levels in Finland in 2008 were somewhat above the target set for 2010 (Finnish Environment Institute 2008a).

Eutrophication due to an excess of anthropogenic nitrogen and phosphorus emissions is a severe problem for all European seas at present, but it is more significant for estuaries and coastal seas, especially in the Baltic Sea (e.g. Elmgren 2001, Rönnberg & Bonsdorff 2004, HELCOM 2009). A common outcome is excessive blooms of algae in surface waters. These nutrients mostly originate from food production. Agriculture and wastewaters from communities are the main polluters. In addition, fish production is an important local polluter, even though it contributes only 1% of the total nitrogen load and 2% of that of phosphorus from Finland to the Baltic Sea (Uusitalo et al. 2007). The impacts of nutrient emissions are not uniform in space or time. The minimum factor varies within the Baltic Sea: in general, nitrogen limits primary production in the outer sea regions and phosphorus in the coastal areas (Moisander et al. 2003). In addition, there are thresholds making the responses of primary producers to nutrient addition nonlinear, and meaning that small changes in nutrient quantities might lead to major consequences in ecosystems (Tamminen & Andersen 2007). Therefore, the specific effects of quantitative nutrient reductions are difficult to predict. The calculated total nitrogen load to the Baltic Sea was 0.204 million tons N in 2005. Atmospheric deposition of nitrogen is an important source of nutrients to the sea, accounting for approximately 30% of the total nitrogen load. However, the calculated total deposition in the Baltic Sea decreased from 1995 to 2005 by 18% (Bartnicki & Fagerli 2008).

1.3 SETTING EMISSION REDUCTION TARGETS

The impacts of most severe environmental problems do not respect national borders. The widely recognized polluter pays principle is not easy to apply when polluters themselves do not suffer from the impacts, or if the polluter is not under the legislative power of the country that suffers. When emissions end up in global or regional “commons” (Hardin 1968), such as the atmosphere or marine ecosystems, strong international agreements are often needed for mitigation. Reduction targets can be set country specifically or by country groups. The implementation of reductions can also occur sector specifically. Many societies, especially small and stable populations with a solid social network and social norms, have also on their own developed various institutional measures for managing resources (Ostrom 2009).

To reduce greenhouse gas emissions, the Kyoto protocol was negotiated in 1997 and came into force in 2005, setting binding reduction targets for those countries that have ratified the protocol for the period 2008–2012. Subsequently, the target of a 20% reduction in emissions by 2020 compared to 1990 levels was agreed upon in the European Union, and country-specific legally binding targets were accepted in 2008 (EC 2008). A new international climate regime was aimed at in Copenhagen in December 2009, yet not achieved. However, it was agreed that to prevent dangerous anthropogenic interference with the climate system, the increase in global temperature should be kept below 2 °C (UNFCCC 2009). The Intergovernmental Panel on Climate Change (IPCC 2007) has recommended that industrialized countries should reduce their emissions to 25-40% below the 1990 level in 2020 and 80-95% below this level in 2050 in order to limit the global temperature growth to 2 °C. The respective target for developing countries would be a 15-30% reduction. Effort-sharing approaches can be set based on simple and transparent top-down methods or more sophisticated and data-oriented bottom-up methods (Sijm et al. 2007). Emission reductions should aim for overall cost-efficiency, but also on equity and fairness between nations. Besides systematic approaches, effort sharing can be based on consensus in the negotiation process. The internal effort-sharing targets of the Kyoto Protocol for the EU Member States were negotiated on the basis of the Triptych approach, incorporating indicators such as the standard of living and level of economic development, differences in economic structure and differences in the fuel mix (Blok et al. 1997, Phylipsen et al. 1998).

To control acidification, the 1979 United Nations Economic Commission for Europe (UNECE) Convention on Long-range Transboundary Air Pollution (CLRTAP) started with a protocol aimed at reducing sulphur emissions by at least 30% of the emission levels of the time, and continued with protocols further cutting sulphur emissions and limiting those of nitrogen oxides. Later, a 'critical loads' approach was taken in the 1988 large combustion plant directive (revised in 2001), in the 1999 protocol to abate acidification, eutrophication and ground-level ozone, and the 2001 National Emissions Ceiling directive (EEA 2005).

Regarding eutrophication of the Baltic Sea, a wide array of both national and international policy actions have been implemented in the Baltic Sea countries in recent years. For instance, the HELCOM Baltic Sea Action Plan incorporates goals for the mitigation of the nutrient load: an 18% reduction in nitrogen and 42% reduction in phosphorus emissions from the average annual level of 1997–2003 by the year 2016 (HELCOM 2007). In 2007, the programme was adopted by the Contracting Parties to the Helsinki Commission[1]. Policies to reduce the nutrient load in the Baltic Sea have set emission reduction targets for the different Baltic countries. Most often, reductions are implemented in different sectors, such as waste management and agriculture.

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[1] The Helsinki Commission (HELCOM) works to protect the marine environment of the Baltic Sea from all sources of pollution through intergovernmental co-operation between Denmark, Estonia, the European Community, Finland, Germany, Latvia, Lithuania, Poland, Russia and Sweden.

1.4 Aims of the study

Population, affluence, technology and the intensity of consumption are fundamental drivers behind environmental change. These factors characterize the historical development, and they can be used as indicators for future development. International trade is becoming increasingly important, as consumption and production are becoming more and more separated in spatial terms.

In this study, four case studies examining macro-level forces that influence emission change were carried out. Changes in population size, affluence, technology and consumption in relation to changes in emissions were considered in these studies. Historical developments in NO_x emissions in Finland (I) and CO_2 emissions in the EU27 (II) in relation to energy use were analysed inside clear country-specific boundaries. In paper III, international trade was included in the analysis: the historical development in nutrient emissions from Finnish rainbow trout aquaculture was investigated in relation to total Finnish salmonid consumption, including imports. Furthermore, the macro-level perspective was applied in scenario analysis (II) and in sharing the mitigation effort among countries (IV) in relation to EU climate policy. The specific aims of this dissertation were to address the following questions:

1. What is the contribution of macro-level drivers: population, affluence, consumption in terms of intensity of use, and technology in terms of emissions intensity on emissions in the recent past, in the case studies?

2. What is the role of international trade, among other above-mentioned macro-level factors, in the development of emissions?

3. What is the applicability of an essential industrial ecology tool, the ImPACT identity, in analysing environmental emissions?

4. How could the macro-level perspective be applied to evaluate and set up emission reduction targets?

2 Approach of the study

2.1 Industrial ecology

Industrial ecology is a research field[2] that studies interaction between industrial systems and natural ecosystems. Industrial ecology visualizes material, energy, and information flowing in industrial systems as they do in ecosystems. In ideal industrial systems, the use of energy and materials is optimized and the generation of waste is minimized. The waste from one process is used as the raw material in another process (Frosch & Gallopoulos 1989). The concept of industrial ecology and an industrial ecosystem was clearly formulated first by Frosch and Gallopoulos in 1989, even though there were some earlier attempts to develop the field (Erkman 1997). It was realized that conventional end-of-pipe technologies to reduce emissions and waste minimization were not necessarily reducing the overall environmental impact (den Hond 2000). A systems perspective was also asked for.

Industrial ecology is a descriptive discipline in the sense that it seeks to characterize and describe human-environment interactions (Lifset & Graedel 2002, 12–13). Industrial metabolism refers particularly to the idea of industrial systems working as natural ecosystems (Ayres 1989). Industrial metabolism can be interpreted as a subcategory of industrial ecology. As a distinction, industrial ecology also attempts to understand how the industrial system works as an interactive system, how it can be regulated and how it interacts with natural systems (see e.g. Johansson 2002, 74).

Besides a theoretical framework, industrial ecology is a normative discipline, as many industrial ecologists are concerned about the potential environmental implications of production and consumption, and are seeking to answer the question of how things ought to be, and to find ways for improvement (Lifset & Graedel 2002, 12–13). Industrial ecology emerged in the 1990s, when the cultural context was appropriate (Erkman 2002). The context within which science occurs, and that individual scientists themselves select the subjects of their study, is heavily normative (Allenby 2006). Graedel and Allenby (2003) stress that mixing philosophical and practical aspects of industrial ecology, is relevant, as "… in the essence of industrial ecology is the combination of technology and society. These interactions as well as human-environment interactions need to be understood. The goals and techniques of industrial ecology need to be placed in the logical framework of industrial ecology." Industrial ecology is neither purely scientific, nor purely technological, but includes elements of both. Conceptually, science is an objective activity that attempts to determine 'what is', and measures its success by its alignment with physical reality

[2] Industrial ecology has been defined as a field, discipline, area of study, and also a discourse when examining broader dialogues around industrial ecology (Allenby 2006).

and data. Technology, on the other hand, is normative and creates that 'which will be', although always in conjunction with the cultural context (Allenby 2006).

The aims of industrial ecology are to close the loop of materials and substances, and reduce resource consumption as well as environmental releases. The core elements of industrial ecology are, according to Lifset and Graedel (2002, 8–9), the use of biological analogy, the use of a systems perspective, the role of technological change, the role of companies, dematerialisation and eco-efficiency, and forward-looking research and practice.

The biological analogy is useful in outlining industrial ecology. In ecosystems the flow of materials is cyclic, the wastes are recycled and energy is cascading. On the contrary, industrial systems often emphasize the throughput of materials. Ecological systems are often based on interaction and interdependence related to the stability of the systems or to the potential of the systems to recover. Industrial systems emphasize independence and competition. However, the analogy is not straightforward, and the differences between ecological systems and human systems must be considered. Biological systems evolve through biology and culture; human systems also through technology. Moreover, industrial systems are dependent on the resources and services provided by the biosphere (Jelinski et al. 1992, Graedel & Allenby 2003). Natural ecosystems on a local scale are often highly inefficient in terms of material and energy use. For instance, the carbon cycle can be considered closed only on a global scale. However, the global natural ecosystem is a model of an almost perfect material recycling and energy cascading system in the long term. During billions of years, the natural system has developed from a linear throughput system to a round-put system with closed material loops and energy cascades (Graedel & Allenby 2003).

Besides the biological analogy, technological change is at the core of industrial ecology. The role of technology in relation to other macro-level factors affecting environmental change has been much studied in industrial ecology. Companies have a role in implementing technologies on a micro-level. Companies are also a potential source of innovation towards more sustainable products and services. The contribution of industrial ecology to regular environmental management is that the analysis crosses borders of countries and goes beyond individual products.

Dematerialization, the reduction of materials or energy in relation to economic output, and decarbonisation, the reduction of carbon emissions in energy production, are two key concepts of industrial ecology (Lifset & Graedel 2002, 10)[3]. Dematerialization reduces emissions, as according to the law of conservation of mass, every material input sooner or later turns up as emissions or waste. However, dematerialization does not necessary imply that wastes are minimized and material cycles are closed. Dematerialization thus lowers the level of industrial metabolism (de Bruyn 2002).

[3] Other definitions also exist for these concepts, see e.g. Tapio et al. 2007

Dematerialisation, decarbonisation and other macro-level drivers of environmental change are examined in more detail in the next chapter.

Industrial ecology is increasingly paying attention to the role of consumption in environmental management and policy (Hertwich 2005b, Lifset 2008). One concept to emerge in industrial ecology is the shift from ownership of products to a service economy, but also more strongly linking environmental impacts to social processes. In addition, the role of policy measures to stimulate sustainable lifestyles, to facilitate sustainable consumer behaviours, and to develop sustainable systems of consumption and production is important (Tukker et al. 2010). Furthermore, issues of complex change, co-evolution, and systemic resilience are consistent with the industrial ecology metaphor, yet still not much studied (Tukker et al. 2010).

Industrial ecology uses several tools from the product level to global analysis. At the process level, industrial ecology looks at the environmental impacts related to life cycles of products and services through life-cycle assessment (Rebitzer et al. 2004, Finnveden et al. 2009), or design for the environment (Hendrickson et al. 2002). Between organisations such as companies and public actors, industrial ecology applies the biological analogy and uses an industrial ecosystem concept, examining how materials, energy and information can flow in these local or regional networks as efficiently as possible (Chertow 2000a). The terms industrial symbiosis, eco-industrial park, eco-industrial networks and eco-industrial estates are also widely used. At the regional or global level, industrial ecology studies flows of materials and energy and uses material and substance flow analyses. Material flow analysis connects the sources, the pathways, and the intermediate and final sinks of a material (Brunner & Rechberger 2004). Based on the law of mass balance, potential leakages and inefficiencies can be detected. An aim is to close the loop of substances and improve the efficiency in material use (Van der Voet 2002). At global or regional levels, industrial ecology uses the IPAT concept to study dematerialisation and the effects of technology as well as changes in population and affluence on changes in the environment (Chertow 2000b). IPAT is used as a method in this study, explained in detail in the methods section and examined more profoundly in the discussion.

Industrial ecology overlaps with many other research fields such as ecological economics, engineering and environmental management. Social sciences such as consumer research are also emerging in the field of industrial ecology. The definition of disciplinary approaches that are ‘in’ the field of industrial ecology is not clear. The subject matter of study, industrial and economic systems and related environmental impacts, does not itself entail simple boundaries. Industry is at least a physical phenomenon, an economic phenomenon, a social and cultural phenomenon, and a source of interaction between human and natural systems (Allenby 2006).

2.2 Macro-level drivers affecting environmental change

The global human population has doubled in the past 40 years or so and reached 6.0 billion in 2000. Urban areas contain half of the world's population, and this proportion is increasing. In addition, household sizes are decreasing (UN 2009). The relationship between population size and especially CO_2 emissions and energy consumption has been extensively investigated. Many studies have shown that the growth in CO_2 emissions is linearly linked with population growth (Bongaarts 1992, MacKellar et al. 1995, Dietz & Rosa 1997, York et al. 2003, Cole & Neumayer 2004). However, this may not always be the case. For instance, Martinez-Zarzoso et al. (2007) observed in a study of 23 European Union countries during 1975–1999 that, especially for the founding members of the EU, the impact of population growth on CO_2 emissions was less than proportional. For new EU countries, however, growth in emissions was relatively faster than that in population size, showing the complexity behind population issues.

Besides population size, population dynamics significantly influence the volume of greenhouse gas emissions (Martinez-Zarzoso et al. 2007, Sherbinin et al. 2007). Age structure has clear effects on energy consumption. In one worldwide study, a higher proportion of working-aged people in the population was found to reduce emissions when levels of affluence were high, but increase emissions at lower affluence levels (Fan et al. 2006). York (2007) reported that an increase in the proportion of elderly people in the population corresponds with an increase in aggregate energy consumption. Changes in age structure are likely to influence the structure of the economy, particularly the composition of production and consumption, as well as the spatial distribution of the population, transportation infrastructure, and social services. Urbanisation and decreasing household size accelerate emission growth (Cole & Neumayer 2004). Population dynamics can also be seen to affect the environment through other variables such as culture, consumption levels, institutions and technology (de Sherbinin et al. 2007). Population projections are important when estimating future emissions and sharing emission reduction targets. However, according to Meyerson (1998), population issues were not considered in the formulation of the Kyoto protocol, because of the complexity of population interactions as well as political issues.

Affluence can be described as income and has been traditionally measured in terms of gross domestic product (GDP) per capita. The Kuznets hypothesis assumes that, along with economic growth, emissions first increase, but then curb down as a nation becomes wealthy enough (see the critical review by Stern 2004). This has, in fact, been shown for a few substances such as national NO_x emissions, but the trend has not been observed for CO_2 (Rosa et al. 2004, Fig. 1). The development of affluence is thus often a strong indication of an increase in CO_2 emissions. For instance, in China during 1981–2002, the main driver for the increase in CO_2 emissions was the growth in per capita GDP. If all other factors had been equal to the 1981 levels, the growth in affluence would have increased emissions by 469%. In reality, the emissions grew by 202% during 1981–2002, partially offset by improvements in emission intensity (Guan et al. 2008). Affluence is also a common indicator of the development and wealth of nations that is used, for example, when aiming at reducing environmental emissions equitably between nations. For instance, the European Commission accepted legally binding Post-Kyoto targets for its Member States in 2008, according to which the emission reduction efforts of those sectors outside the emission trade scheme would be divided between Member States based on GDP per capita criteria (EC 2008).

Improving the intensity of consumption or the dematerialisation of economies in industrial ecology refers to reducing material or energy use per unit of service output. The reverse, increasing output per unit of materials used, is defined as eco-efficiency. Dematerialisation refers to lowering the level of industrial metabolism, rather than closing cycles of materials or energy (de Bruyn 2002). However, aiming at dematerialisation does not always lead to a relative decrease in the use of resources. For instance, in Western Europe, overall energy use has risen despite improvements in energy efficiency (Holm & Englund 2009). Efficiency gains lower the energy prices, and are then used to increase consumption and energy services (Herring 2006). This rebound effect has particularly been studied in energy economics. Greening et al. (2000) estimated in a review that the rebound effect for residential energy uses would be around 0-0.5% for a 1% increase in energy efficiency, greatly depending on consumer awareness. The results from separate studies may vary significantly depending on the boundaries used to describe the rebound effect. For instance, a relative 1% increase in technical energy efficiency was found to increase household CO_2 emissions by 0.25% in a study by Brännlund et al. (2007). The Jevons paradox, or backfire, refers to the case when the rebound effect is greater than 100%, exceeding the original efficiency gains (Alcott 2008). Besides direct rebound effects, there are often unintended negative and positive side-effects, as well as positive behavioural and technological spill-over effects related to energy efficiency (see e.g. Hertwich 2005a). A country’s overall energy efficiency is also influenced by international trade. The import of energy-intensive products reduces the need for domestic production and the environmental effects are often shifted to countries with low energy efficiency (Herring 2006).

Improving technology is also within the scope of industrial ecology. At the macro level, as in this study, “technology” refers to the relationship between emissions and energy or material use. In particular, decarbonisation refers to reducing the carbon emissions per unit of energy consumed (Nakicenovic 1996). This definition is used in this study, although decarbonisation can also be defined as improving the ratio of carbon emissions to the unit of GDP produced. Emission intensity of use is often improved merely by technical solutions. However, improvements in the intensity of emission are not necessarily actual technical developments, but can also reflect changes in the structure of the system. Moreover, in a country-specific analysis, they can reflect changes in international trade, in cases where the most emission-intensive production is shifted across borders.

Regarding both the intensity of use and technology, changes may occur due to trade. For instance, tightening of regional environmental regulation in one place may force energy intensive and emission intensive industries to relocate in countries without emissions commitments, and lead to a carbon leakage (IPCC 2007). According to Peters and Hertwich (2008b): "…a policy-relevant … approach to carbon leakage is to quantify all emissions generated by each country in the production of goods and services that are traded internationally: the total emissions embodied in trade." This leakage effect may even increase the total emissions. An estimated 5.3 gigatons (Gt) of embodied CO_2 emissions were shifted around the globe due to international trade in 2001. This was 22% of the respective global carbon dioxide emissions. In general, developed countries were net importers of CO_2 emissions with exceptions such as Finland (Peters & Hertwich 2008a). A detailed study shows that half of the environmental impacts of Finnish economy are due to manufacturing of imported products (Seppälä et al. 2009). With increased international trade, the indirect environmental impacts are difficult to determine because a proportion of the emissions occur in different geographical regions.

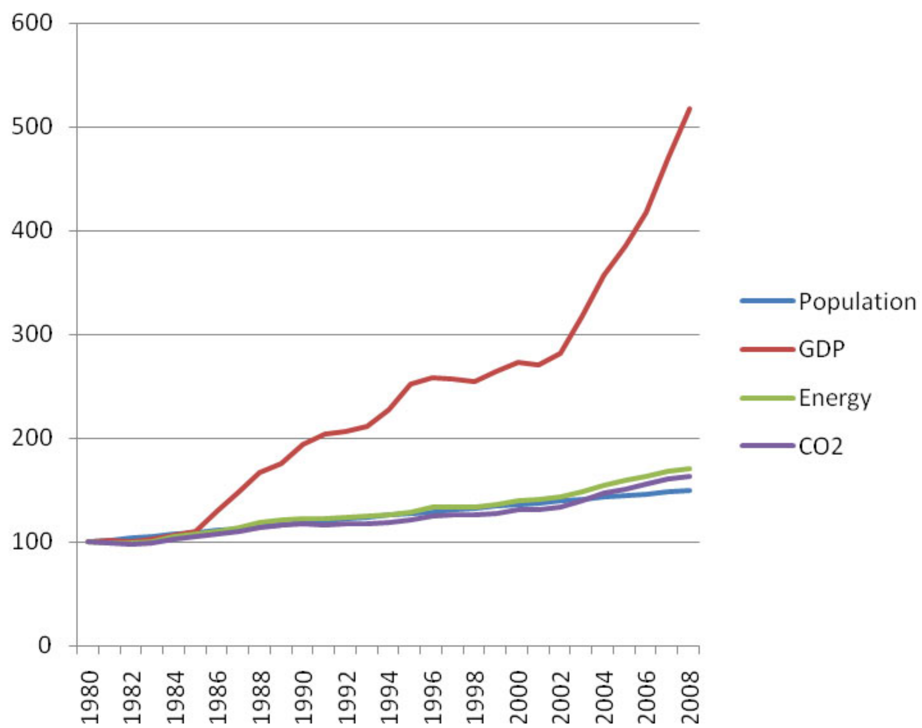

Figure 1. Changes in world population, GDP (current prices) (IMF 2009), Primary energy consumption (BP 2009) and CO_2 emissions (BP 2009) during 1980-2008. (1980=100)

3 MATERIAL AND METHODS

3.1 IMPACT ANALYSIS

In this study, ImPACT decomposition analysis was used to identify the macro-level drivers affecting emissions (Waggoner & Ausubel 2002). The ImPACT formula is also known as the Kaya identity (Kaya 1990) and is a reformulation of IPAT analysis, first introduced by Paul Ehrlich and John P. Holdren. Ehrlich and Holdren (1971) presented the original equation and emphasized the importance of demographic aspects in relation to environmental problems. They divided the impact into population and per capita impact. Barry Commoner (1972) debated the issue and drew attention to the role of production, including technology in the equation. In ImPACT, also the role of consumption is included in a narrow sense. The ImPACT identity is used to describe and predict the impact of changes in population size, affluence, technology and in addition, consumer intensity on environmental changes. In the ImPACT identity, the total environmental impact I is determined as the product of four drivers, shown in equation (1):

$I = P \times A \times C \times T$

where P is measured by the population, A by GDP/capita, C by use/GDP, and T by impact/use. Lowercase letters *p*, *a*, *c* and *t* represent the annual percentage changes in the four drivers, which add to the change in the impact I. Thus, the identity analyses the contribution of each of the four drivers to the change in the impact.

Growth rates can be calculated using equation (2),

$\alpha_{i,j}e^{r} = \alpha_{i+1,j}$ (2)

transforming to equation (3),

$r = \ln(\alpha_{i+1,j}) - \ln(\alpha_{i,j})$, (3)

where α represents the value of the ImPACT variable in one year, i represents the year, *e* the natural logarithm, j the variables *p*, *a*, *c* and *t*, and r the annual growth rate. The sum of the growth rates of j equals the change in the impact, and each component's share of the total can be determined. By taking the logarithm, the formulation ensures that all variables add up to 100% (Herendeen 1998). For small to moderate changes between two years, taking logarithms implies that the sum of the percent changes in each variable closely approximates the percent change in emissions between those two years (Zhang 2000).

In the identity, the factors relate to each other. There is often a strong ‘mirroring’ effect, especially between the changing affluence and intensity of use. For instance, affluence decreases in a recession but energy systems adjust only slowly in the short term; thus, energy intensity tends to increase (Waggoner & Ausubel 2002). The consumption of resources can be connected to income with an income elasticity *b*. Per capita consumption A × C is proportional to A^b, and so $a + c = b \times a$, and then income elasticity $b = c/a+1$. If elasticity $b = 0.4$, then an annual rise in income of 1% raises per capita food demand by 0.4%. If $b = 0.4$, then the elasticity of c is −0.6. When the elasticity b of consumption per person is less than 1, the elasticity of intensity of use c will be a negative $(b - 1)$.

The IPAT and ImPACT frameworks have been used to analyze several environmental issues (Ausubel & Waggoner 2008). For waste management the model has been used by Sokka et al. (2007) and for the forest sector by Waggoner and colleagues (1996) and Wernick et al. (2000), among others. Raupach et al. (2007) studied the trends and drivers of CO_2 emissions at the global and regional scale, decomposing emissions to population, affluence, the energy intensity of the gross domestic product and the carbon intensity of energy consumption. Other analyses for CO_2 emissions are included in the European Union GHG emission inventory reports (EEA 2007a), and have also been conducted by Kawase et al. (2006), among others. The framework has additionally been used in projecting future CO_2 emissions by O'Neill et al. (2001) and by Nakicenovic and Swart 2001) in the IPCC emission scenarios. Bongaarts (1992) also used the framework for emission projections, including land-use changes in the equation. The approach has also been recently applied to study the contribution of different ImPACT variables in several sectors in various scenarios to achieve CO_2 emission reduction targets (Agnolucci et al. 2009). In this study, four factors, that are less studied earlier, are examined. Here, the tradition of ImPACT is continued and new information is developed by 1) using long historical time series, 2) by evaluating the stringency of environmental targets, 3) by revealing totally new areas of study in the tradition such as evaluating salmon consumption and aquaculture industries and, 4) incorporating international trade in the framework.

3.2 SYSTEM DESCRIPTION

Four diverse case studies (in papers I-IV) were included in this study. The studies cover different time spans and the historical time series were essentially determined by the availability of reliable data. Paper I focuses on the development of NO_x emissions inside Finnish borders during 1950–2003. Paper II addresses the development of CO_2 emissions within individual Member States of the European Union and in the EU as one closed region during 1993–2004. In paper III, spatial system boundaries are expanded. The paper analyses total salmon consumption in Finland in relation to nutrient emissions from domestic rainbow trout aquaculture in Finland and includes imports of salmon. The time span covered is 1980–2007.

Scenario analyses are presented in papers II and IV, using a time frame up to 2020. Paper IV discusses how the results from production-based emission inventories could be applied in a scenario analysis, questioning the assumptions of forecasts and discussing the use of the same national system boundaries for producing and mitigating emissions, separated from actual consumption.

Table 1. Time frames, studied regions, emissions and related drivers in papers I-III

	Paper I	Paper II	Paper III
Time	1950–2003	1993–2004	1980–2007
Region	Finland	27 European Union Member States	Finland
I	NO_x	CO_2	N load, P load to waters
P	population	population	population
A	GDP/capita	GDP/capita	GDP/capita
C	Energy/GDP	Energy/GDP	salmonid consumption/ GDP
T	NO_x/Energy	CO_2/Energy	N load/ domestically produced rainbow trout, P load/ domestically produced rainbow trout
D	not included	not included	domestically produced rainbow trout /salmonid consumption in Finland

I NO_X EMISSIONS FROM FINNISH ENERGY CONSUMPTION

Driving forces of emissions of nitrogen oxides (NO_x) from energy production in Finland were analyzed in paper I. Changes in NO_x emissions were studied through changes in population, affluence (GDP/capita), consumption (energy/GDP) and technology (NO_x/energy). The energy system covered the combustion of fuels inside Finnish borders, including transport. The total energy consumption of Finland was included, even though the emissions are only generated in the combustion processes of certain fuels. Thus, changes in technology (t) imply changes in combustion processes (efficiency, type of process, etc.), but also structural changes, such as changes in the energy mix. In combustion, all nitrogen in the fuel is released to the air. During combustion, both nitrogen in the fuel and nitrogen from combustion air (N_2) are transformed into harmful emissions of N oxides (NO_x) or nitrous oxides (N_2O). However, N can also leave the energy system after combustion as harmless molecular N_2.

II CO_2 FROM ENERGY CONSUMPTION IN THE EUROPEAN UNION

Changes in CO_2 emissions in the EU27 were studied by countries addressing changes in population, affluence (GDP/capita), consumption (energy/GDP) and technology (CO_2/energy). Total energy consumption and CO_2 emissions from the combustion of fossil fuels were included. The macro-level perspective in scenario analysis was presented in order to estimate the stringency of the European Union target of a 20% cut in emissions from 1990 levels by 2020. Population scenarios up to the year 2020 were applied as prepared by Eurostat and simple economic scenarios were developed (see 3.3) in order to estimate a baseline for the required improvements in dematerialization and decarbonisation.

III SALMONID CONSUMPTION

The system under study in paper III was the Finnish salmonid consumption and production system. Nutrient load was determined as the product of five drivers:

$I = P \times A \times C \times T \times D$,

where I is nutrient load (nitrogen/phosphorus) from rainbow trout aquaculture, P population, A affluence (GDP/capita), C total consumed salmonids per GDP, T technology as nutrient load per unit of domestic rainbow trout (i.e. specific discharge) and D the share of domestically produced rainbow trout of total salmonid consumption in Finland.

Only emissions from Finnish rainbow trout aquaculture were included and not those of other Finnish salmonids, as aquaculture introduces the only human-induced nutrient load in Finland. The consumption of all salmonids was considered jointly. In the study, salmonids included rainbow trout, Atlantic Salmon, Baltic Salmon and Trout. Total rainbow trout production was included, although a small proportion of the fish produced was exported (Finnish Game and Fisheries Research Institute 2001, Finnish Game and Fisheries Research Institute 2008a).

IV EFFORT SHARING

In paper IV, top-down macro-level figures were used to set the emission reduction targets for the EU Member States. Four effort-sharing scenarios were generated for emission reduction in sectors outside the emission trade scheme (non-ETS)[4], such as agriculture and waste management. In Scenario 1, the annual rate of change in GHG/GDP was assumed to be the same in all Member States during 13 years in 2008-2020. In Scenario 2 it was assumed that GHG/GDP converges for all countries by 2020. In Scenario 3 it was assumed that national annual rates of GHG/GDP development would be the same as they were in 1993-2005. In order to reach a reduction of 20% by 2020, an additional reduction was required. This additional annual reduction was set as constant over time and the same for all countries in percentage terms. In Scenario 4 it was assumed that per capita GHG emissions converge for all countries by 2020. The reduction in the non-ETS sector was determined through reductions in the ETS sector. In the ETS sector, each country was hypothetically set to reduce its emissions by the same proportion compared to their verified ETS sector emissions in 2005.

A few test runs were conducted for all scenarios to analyze certain sensitivities involved in the results. In the test runs, the base year (starting point for reductions) for emissions and GDP was changed. In addition, the period for ETS reductions was changed from the latest verified emissions to allocated future emissions. In addition, ETS reductions as a proportion of the total reduction were changed. Moreover, GDP and population forecasts were varied.

3.3 DATA

Here, an overview is provided of the calculations and data sources. A more detailed description of the data sources is presented in the respective papers.

In paper I, the total amount of N oxides (NO_x) was calculated based on work by Statistics Finland (2004a, years 1980–2003), Savolainen and Tähtinen (1990, years 1950–1979 estimation). GDP data adjusted to 2000 prices were acquired from Statistics Finland (2005a). Population data were based on Statistics Finland (2005b). Energy data were based on information from Statistics Finland (2004b; years 1970–2003), the Ministry of Trade and Industry in Finland (1977; years 1960–1969) and Myllyntaus (1980; estimates for years 1950–1959).

[4] ETS stands as an abbreviation for emission trade scheme, whereas non-ETS refers to all the non-trading sectors.

In paper II, the study period covers the years 1993–2004, with extensive panel data available for the EU27 Member States at the time of the research. Data for CO_2 emissions excluding land-use, land-use change and forestry were obtained from the EEA (2007b). Historical population data for the years 1993–2006 were extracted from the Eurostat database (2007a). Energy consumption data for the years 1993–2005 were extracted from Eurostat (2007b). Data for GDP measured in purchasing power parities were obtained from the Penn World Table for the years 1993–2004 and are reported at constant prices in year 2000 international dollars (Heston et al. 2007).

In the scenario analysis in paper II, for the future development of the population, three projections were adopted from Eurostat (2007a). CO_2 and energy consumption values for the years 2006–2008 were estimated by continuing the average development trend in percentage terms, observed in the preceding five years of historical data. The time series of real GDP was extended to the years 2005–2006 using real GDP growth rates as reported by Eurostat (2007c), and to 2007–2008 by using forecasts reported in the same source. For economic projections of the development of total GDP after 2008, countries were divided into four groups based on their level of affluence (GDP/capita) in 2006. The GDPs of the countries in the richest group was set to grow at five different rates per year (baseline 2%/y). The other three groups of countries converged to the average affluence level of the richest group at differing time spans, depending on their initial level of affluence.

In paper III, data on fish production and the nitrogen and phosphorus load from rainbow trout aquaculture for 1988, 1989 and 1991–2007 were obtained from the Finnish Environment Institute (2008b). In 1988, the procedure for collecting statistics changed. For 1980–1987 and 1990, the production figures were taken from the Finnish Game and Fisheries Research Institute (2001). Nitrogen and phosphorus emissions were estimated from these production figures, based on a coefficient used by Karttunen and Vielma (1993). Data on other domestic salmonids were obtained from the Finnish Game and Fisheries Research Institute (2008b) and the import of salmonids from the Finnish Game and Fisheries Research Institute (2008a). The population data were based on Statistics Finland (2008a). The GDP data were obtained from Statistics Finland (2008b).

In paper IV, the historical data for greenhouse gas emissions and GDP, as well as forecasts for population growth in the different EU Member States were derived from the Eurostat database (2008). Forecasts of economic development were carried out according to a model described in paper II. GDP estimates for the non-ETS sectors were used in the calculation. The approximated GDP share of the Emission Trading Scheme (ETS) sectors was roughly based on Eurostat (2008) GDP data. Required GHG emission intensities were compared to recent historical development in the scenarios. Historical developments in GHG/GDP during 1993-2005 were calculated for total GDP. Non-ETS GHG estimates for 1993 were based on Eurostat (2008). GDP data for 1993 were taken from the Penn World Table (Heston et al. 2007).

4 RESULTS

4.1 THE EFFECT OF MACRO-LEVEL FORCES ON THE HISTORICAL DEVELOPMENT OF EMISSIONS (I,II,III)

Average annual percentage changes in each studied driver add to the change in emissions. Increasing affluence was the main driver behind the growth in nitrogen oxide emissions in the Finnish energy sector during 1950-1980 (paper I). Affluence grew by 4 %/year and NO_x emissions increased by approximately 5%/year during the same period. In the 1980s and 1990s, due to progress in technology (NO_x/energy), the emissions started to decline (Figure 2).

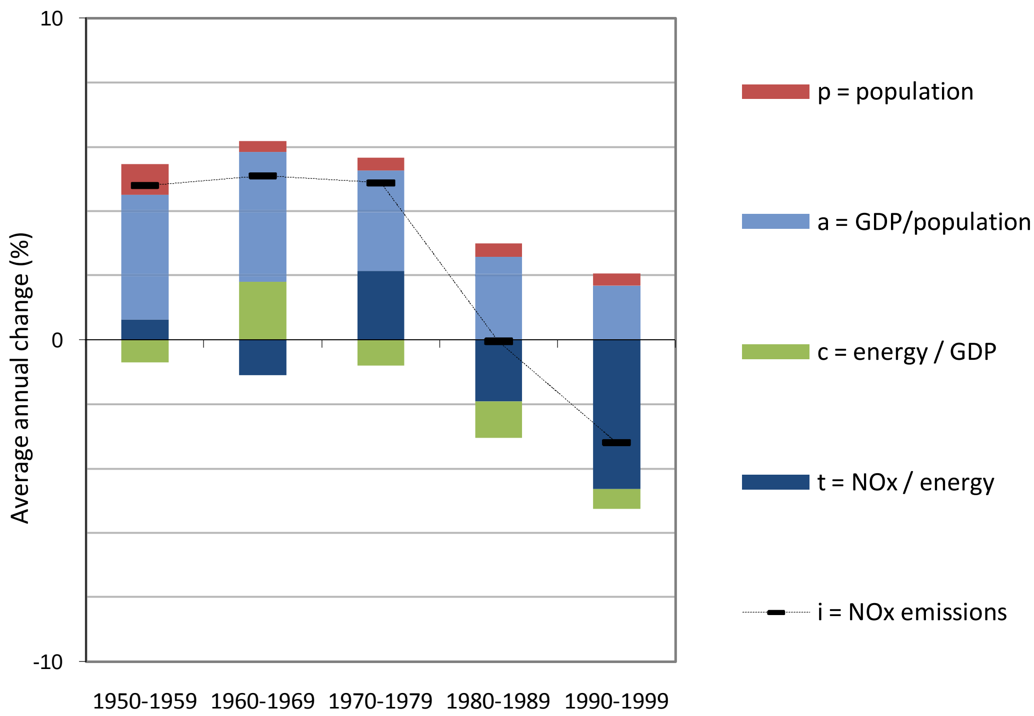

Figure 2. Effect of population, affluence, intensity of consumption and technology on nitrogen oxide emissions in Finland, 1950–2000.

Changes in the energy intensity of the economy (energy/GDP) and technology (CO_2/energy) had a negative impact on fossil emissions of CO_2 in Europe during 1993–2004, which decreased on average by -1.5% and -0.7%/year, respectively (paper II, Fig. 3). However, affluence grew on average by 2.2%/year, and the population by 0.2%/year, more than offsetting the efficiency gains. In the EU15[5], emissions increased at a rate of 0.69%, but the emissions in the 12 New Member States (NMS12)[6] decreased on average by 1.27% annually. Both energy intensity and technology variables were negative in the EU15 states. However, only in the new member states were declining trends in c and t sufficient to compensate for the impact of strong economic growth. A negative trend in the population also slightly contributed to the declining trend in emissions in the NMS12. The EU15 accounted for almost 80% and 90% of the population and economic output, respectively, of the entire EU27 in 2004 and dominated the overall trend. In NMS12 countries, although the rates of dematerialization and decarbonization were high, absolute figures for the energy intensity of the economy and carbon intensity of the energy system were about 40% less advanced than the corresponding estimates for the EU15.

The development of emissions and their drivers varied markedly between members states of the European Union. Changes in energy intensity varied the most, on average from -5.9% to 1.9% annually. Affluence growth also varied considerably, from 0.9% to 6.9%/year, and the average change in technology from -3.1% to 1.3%/year. Population growth did not vary so much between countries, from -0.9% to 1.3%/year.

The increasing intensity of salmonid consumption was the strongest driver for the escalating nutrient load from marine rainbow trout aquaculture in Finland during 1980-2007 (Fig. 4a-b). Affluence was also an important driving force. The nitrogen load peaked in 1989, and that of phosphorus in 1990. The total nitrogen load increased between 1980 and 2007, while the phosphorus load changed only slightly. The production technology of domestic rainbow trout aquaculture (T) had a negative impact on emissions, most strongly for phosphorus. The change in the share of domestically produced rainbow trout of total salmonid consumption in Finland (D) was a major driving force to decrease emission, especially during 2000–2007.

[5] Austria, Belgium, Denmark, Finland, France, Germany, Greece, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden

[6] Bulgaria, Cyprus, Czech R., Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovak, R., Slovenia

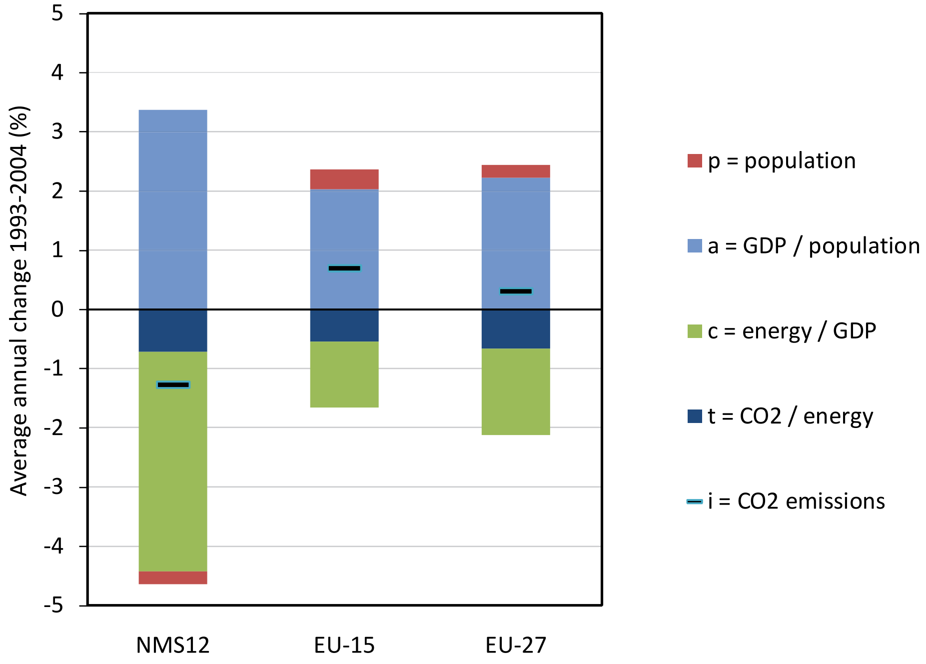

Figure 3. Effect of population, affluence, intensity of consumption and technology on carbon dioxide emissions in the European Union (EU27), the EU15 and the 12 New EU Member States in 1993–2004.

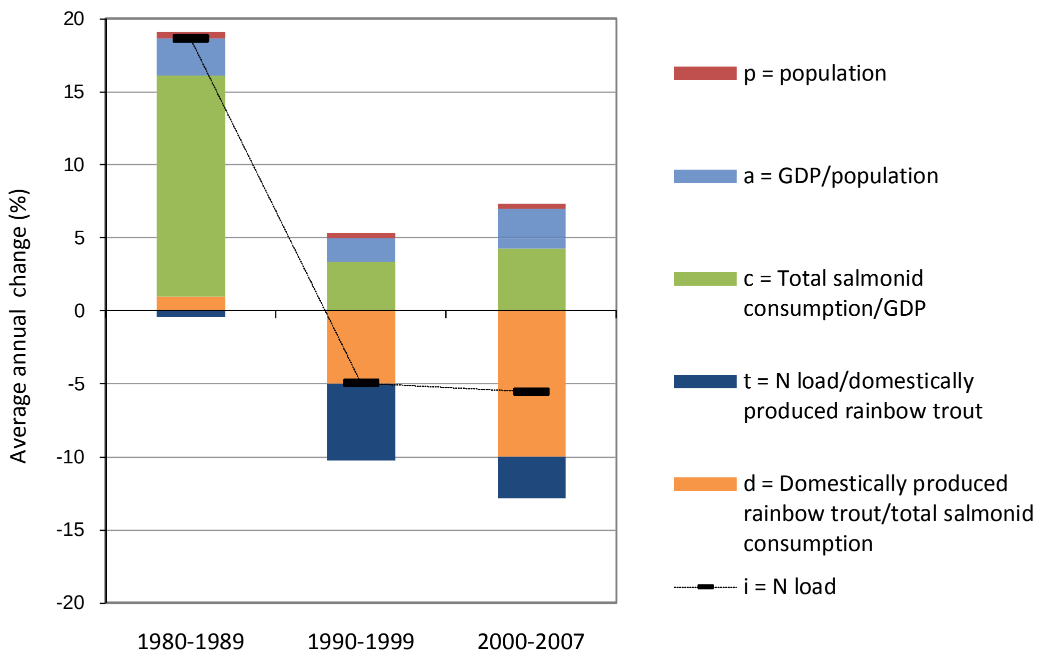

Figure 4a. Effect of population, affluence, intensity of salmonid consumption, domestic aquaculture production technology and the share of domestically produced rainbow trout of total salmonid consumption in Finland on the nitrogen load from aquaculture in 1980–2007.

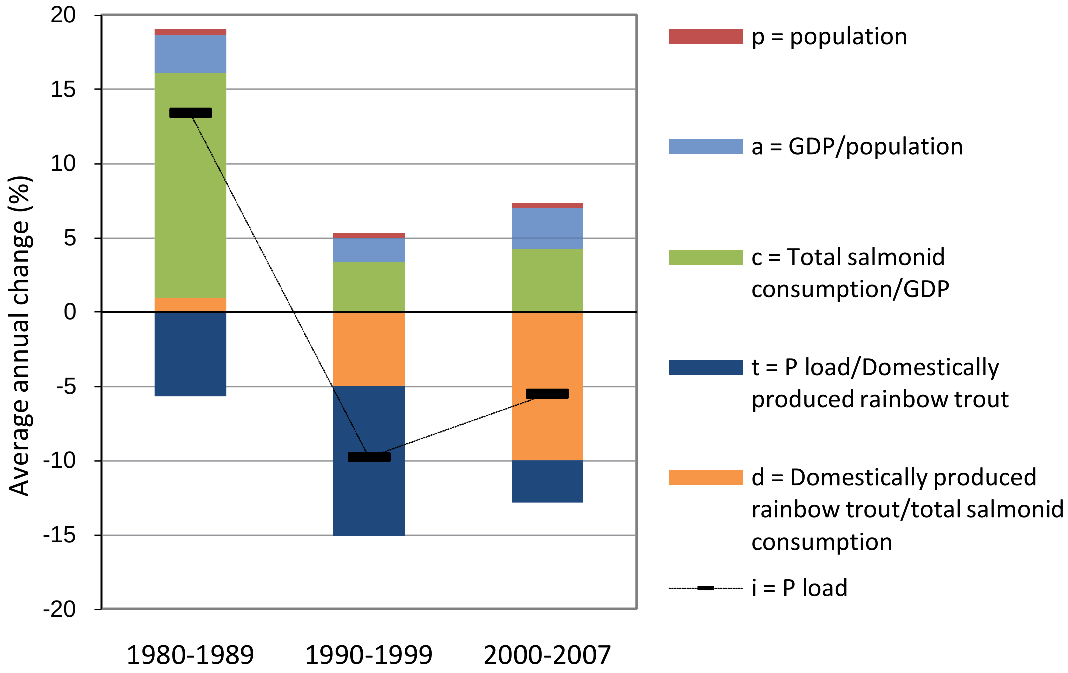

Figure 4b. Effect of population, affluence, intensity of salmonid consumption, domestic aquaculture production technology and the share of domestically produced rainbow trout of total salmonid consumption in Finland on the phosphorus load from aquaculture in 1980–2007.

4.2 COMBINED ANALYSIS OF THE PAST DEVELOPMENT (I, II, III)

In three papers (I-III), the historical development of emissions and changes in macro-level forces in Finland during the 1990s were included. When comparing diverse environmental emissions and uses, differences can be observed (Table 2). On average, the emission intensity of energy use (*t*) decreased annually for NO_x emissions, but not for CO_2. Technology in aquaculture improved strongly. Furthermore, imports of salmonids (*d*) increased, reducing the markets of domestic salmonid production. Dematerialisation occurred in relation to energy use (*c*), whereas the intensity of salmonid consumption increased.

The calculated income elasticities of use ($b=c/a+1$) illustrate the relative development in use with respect to affluence changes. Income elasticity for energy in the studied cases was 0.4 (II) and 0.6 (I) for slightly different time spans. Income elasticity for salmonid consumption was around 3 (III). As incomes increased, energy use increased by half as much in relative terms, but salmonid consumption increased three-fold.

Table 2. The average annual percentage changes in emissions and macro-level drivers in the 1990s in Finland (%/year). Energy-related CO_2 emissions were examined in paper II, and energy-related NO_x emissions in paper I. Nutrient emissions from aquaculture production were assessed in paper III. Note the slightly different time spans.

	Emission	Time	*i*	*p*	*a*	*c*	*t*	*d*
Energy (I)	NO_x	1991-2000	-3.2	0.4	1.7	-0.6	-4.6	
Energy (II)	CO_2	1993-2004	1.8	0.3	3.5	-2.1	0.0	
Salmon (III)	N-load	1990-1999	-4.9	0.4	1.6	3.4	-5.3	-5.0
Salmon (III)	P-load	1990-1999	-9.7	0.4	1.6	3.4	-10.1	-5.0

i = changes in emissions, *p* = changes in population, *a* = changes in affluence, *c* = changes in economic intensity of use, *t* = changes in technology, *d* = changes in domesticity ratio. Changes in the domesticity ratio were disaggregated from changes in technology in paper III.

4.3 Macro-level perspective for future emissions (II, IV)

In the European Union, reducing CO_2 emissions 20% below the 1990 level by 2020 would require the annual decarbonisation and dematerialization rate to be between -4.2% and -5.5% on average during 2008–2020 (paper II). This is around two-fold greater than the average annual rates of change in decarbonisation and dematerialisation that occurred in the EU27 during 1993–2004.

The macro-level perspective in sharing emission reduction commitments between European Union Member States was examined in paper IV with respect to achieving the 20% reduction in GHG emissions below 1990 levels within the European Union by 2020. Only the sectors outside emission trade, such as transportation, housing, services and agriculture, were considered. The overall variation among EU countries in the required reduction targets was found to be large, although the variation between scenarios was moderate for a few large EU countries (Figure 5). The required country-specific reductions would depend on the applied principle of effort sharing, the allocation of reductions between ETS and non-ETS sectors, the selected base year for GDP and emissions, and especially on the economic forecasts used.

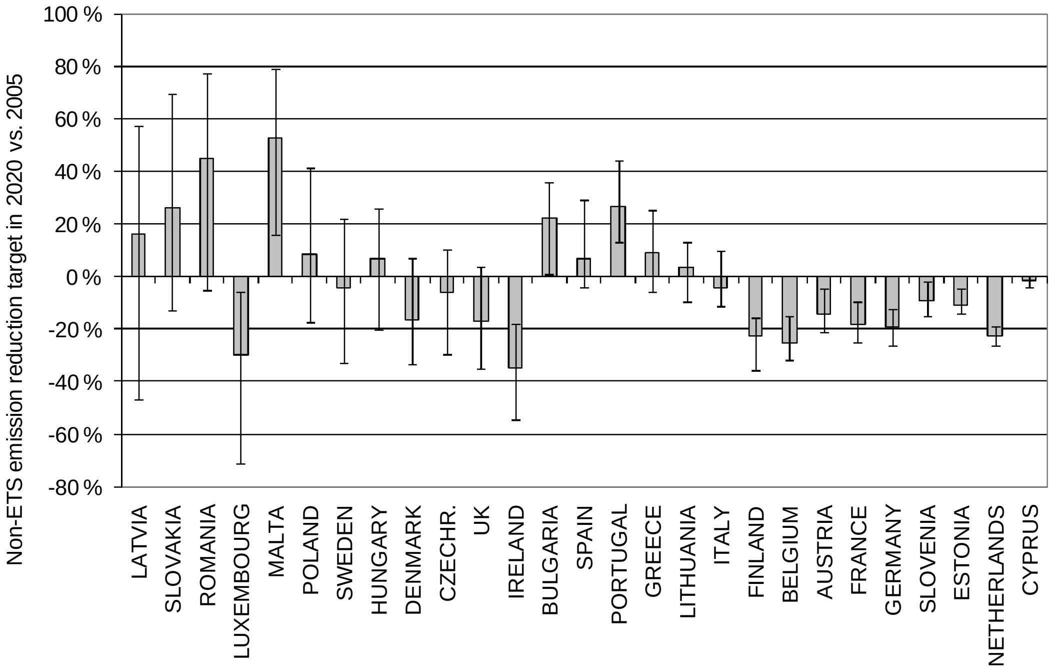

Figure 5. Average change in non-ETS emissions in different scenarios for 2020 in comparison with 2005. Error bars represent the variation range (min and max) in terms of percentage points. Countries furthest left have largest variation between scenarios.

5 DISCUSSION

5.1 DEVELOPMENT OF EMISSIONS

Affluence growth was a significant driver for the development of emissions in the three historical cases examined. During the study periods, the growth in Finnish NO_x emissions (1950–2003) and the Finnish nutrient load from aquaculture (1980–2007) curbed. The same development was not observed for European energy-based emissions of CO_2 during 1993–2004. This is in line with the findings of Rosa et al. (2004) and Raupach et al. (2007), among others.

Climate policy has affected environmental emissions only in the recent past. The Kyoto protocol, setting binding targets for industrialised countries to reduce GHG emissions, was adopted in 1997 and entered into force in 2005. The first period of commitment for the ratified countries is from 2008–2012. Prior to binding climate policies, other environmental conventions were developed. For instance, the Convention on the Protection of the Marine Environment of the Baltic Sea Area was already negotiated in 1974 and came into force in 1980. Since 1980, nutrient emissions from point sources have decreased, including those from Finnish aquaculture and emissions of nitrogen oxides.

A few factors contributed to the lowering of NO_x emissions in Finland. In the 1980s, nuclear power replaced coal-fired electricity generation. The shares of natural gas and black liquor in the fuel mix also increased. The cleaning of nitrogen oxides from industrial flue-gases markedly improved, especially in the 1990s. In the second half of the 20th century, most NO_x emissions were associated with traffic. The declining trend of NO_x in the 1990s was mainly the result of improved automobile technology, as the proportion of cars with catalytic converters rose (Statistics Finland 2000). Technology thus acted on many fronts to reduce nitrogen oxide emissions, despite an increase in energy consumption and also in the total nitrogen flow in the energy sector.

With regards to European energy-based emissions of carbon dioxide during the period 1993–2004, the changes in the energy mix contributed to the improving technology in terms of CO_2/energy. In addition, the relative share of CO_2-intensive fuels, such as coal and oil, in energy consumption declined and the shares of natural gas and nuclear increased (Eurostat 2007b). However, economic growth was strong during the period, resulting in increasing total emissions. In the NMS12, the strong lowering of energy intensity reflected structural change and can be attributed to the growing GDP rather than to decreasing energy use. Services grew faster than did the more energy-intensive sectors such as manufacturing and primary production. The energy consumption of manufacturing and primary production declined, as did the energy consumption of households. In the EU15, dematerialization progressed less well than in the NMS12. The manufacturing sector achieved gains in energy efficiency, while primary production did not. The relative share of the service sector increased. The value added in the service sector was the main driver of economic growth in the EU15. The intensity of energy use in the service sector improved the most out of all the sectors. In the EU15, the energy mix changed on lowering the technology variable.

Considering salmonid consumption in Finland, the nutrient load from domestic aquaculture decreased as the technology improved. Nutrient efficiency began to strongly increase in the 1990s due to the development in feed composition and improvements in production and feeding practices (Karttunen & Vielma 1993, Abbors 2000). The amount of salmonids consumed per GDP increased. Consumers became increasingly aware of the positive health impacts of fish (Rickertsen et al. 2003; Allais & Nichèle 2007). Farmed salmon spread internationally and altered the market structures (Abbors 2000, Setälä et al. 2003). In the early 1990s, Atlantic salmon from Norway was introduced to the Finnish market, where it competed with domestically produced rainbow trout (Finnish Game and Fisheries Research Institute 2001). The consumption of salmon grew 3 times faster than per capita affluence during the 1990s. Salmon consumption was a luxury in economic terms during the study period[7]. The income elasticity of food in general in rich countries is typically about 0.3; thus, when income increases by 10%, food consumption increases by 3% (Searle et al. 2003).

5.2 The ImPACT identity as a tool

The ImPACT method, or IPAT in its basic form, identifies the key drivers behind emissions. When applied to data for multiple time periods, it can be used to reveal historical pathways of changes in several macro-level forces, or to evaluate or to assess the development that is required to attain certain environmental targets as shown with several cases in this study. The results are transparent and the availability of data for this kind of macro-level analysis is usually good.

The ImPACT identity reflects many of the core elements of industrial ecology defined by Lifset & Graedel (2002, 8-9). The systems perspective is present in ImPACT, as the most essential macro-level forces affecting environmental change are included. The implications of setting system boundaries are discussed in more detail in the next chapter. In addition, industrial ecology examines the environmental impacts of the technological society on the one hand, and the role of technology in solving the environmental problems on the other. The original IPAT identity stems from this discussion (Commoner 1972). Dematerialisation, a key concept of industrial ecology,

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[7] Luxury in economics is defined as a good with income elasticicy > 1. Thus, consumption of the good increases more than relative incomes. The price of salmon was not examined in the study.

is measured in the variable C (use/GDP) in ImPACT or T (environmental impact/GDP) in IPAT. Reducing environmental impact through improved technology and increasing dematerialisation is aimed at (Waggoner & Ausubel 2002). ImPACT can be used to evaluate environmental targets and predict future development in environmental change with the help of predicted changes in macro-level drivers. Thus, a forward-looking perspective can be applied with ImPACT. All in all, IPAT and ImPACT identities have been referred to as key elements of industrial ecology (Chertow 2000b, Graedel & Allenby 2003).

However, the ImPACT concept does not apply the principles of the biological analogy. Closing the loops of materials and substance flows cannot be studied using the IPAT identity. Also, as the method is often applied to aggregate data, it cannot be used to identify the location of societies' emission sources, or the potential for the largest emissions reduction.

ImPACT analysis deals with only one environmental impact, or emission, at a time. Techniques that reduce emissions in one place may cause diverse environmental impacts elsewhere (Ehrlich & Holdren 1971). In the cases studied here, other environmental impacts than those included, should not be discarded when evaluating the environmental performance of food or energy systems in a more complete manner. Lowering the technology variable (e.g. emissions/use) often has diverse impacts on the environment. In the case of energy, the impacts of imported electricity, nuclear energy, renewable fuels and hydropower must also be considered. In assessing salmonid consumption in Finland, various environmental impacts due to the farming of Atlantic salmon in Norway due to increasing imports of salmon must be recognized.

ImPACT analysis can be complemented with substance flow analysis, as was done in paper I. A substance flow analysis supporting paper III has also been conducted (Asmala & Saikku 2010). With substance flow analysis, the magnitude of all the flows related to one substance can be examined (Van der Voet 2002). Although substance flow analysis only considers the total mass related to one substance, a life-cycle assessment can, for instance, be additionally carried out to calculate the variety of environmental impacts related to the substance flows (Antikainen 2007). Multidimensional analysis for policy-making purposes, integrating for instance life-cycle assessment, material-flow analysis and the use of system models alongside IPAT analysis, has also been recommended (Huppes & Ishikawa 2009). However, detecting all the flows and related environmental impacts of one substance may not always be necessary.

The eventual impact of emissions is tempered by the capacity of the environment and the threshold for its ecological impact. In addition, the impacts are often delayed in time. The emissions examined in the cases in this study behave differently. Emissions of nitrogen oxides spread regionally and may drift hundreds of kilometres away from their origins. The carrying capacity for NO_x emissions can vary spatially to a considerable extent. Greenhouse gas emissions have the same impact on global warming regardless of where they are emitted. Time dynamics play a role and greenhouse gases differ in their duration in the atmosphere. Thresholds also exist, and the eventual intensity of impacts due to climate change are not linear across time (Lenton et al. 2008). The nutrient emissions to the Baltic Sea from aquaculture are local and impacts on eutrophication are strongly determined by the responses of the aquatic ecosystem (Tamminen & Andersen 2007). In addition, thresholds are difficult to identify and define, complicating policy-making (Lyytimäki & Hildén 2007). To study reduction measures for mitigating global warming, eutrophication or acidification, other emission sources than those studied here must naturally be considered, and case specifically.

A number of other country-specific features such as the level of urbanization and industrial structure are not inherent in the ImPACT model. However, the formulation can be disaggregated into as many variables as desired. For example The European Environment Agency (EEA 2007a) has used decomposition analysis for different sectors of the economy. For instance, country-specific household emissions are determined by the developments in population size, household size, final energy consumption per household, the share of fuel in final energy consumption, the share of fossil fuels from total fuels, and the carbon intensity of fossil fuels. The proportion of employed people in the population has also been examined separately from the total population (Vehmas 2009).

Some industrial ecologists, systematically looking for ways to minimize environmental harm, have taken an interest in consumption, a term that was not included in the original IPAT identity. The motivation for the reformulating of the IPAT identity into the ImPACT form was an attempt to include consumption, or the "consumer's lever", in terms of the economic intensity of use (Ausubel & Waggoner 2008). In this way, some of the criticism that the IPAT identity in its basic form, only including the variables population, affluence and technology, ignores behaviour choices (Schulze 2002, Roca 2002) could be overcome. However, this "consumption", or intensity of use does not describe consumption as such, but also includes structural changes. In any case, it must be noted that in the ImPACT model, consumers influence emissions through all the four macro-level drivers (Saikku 2009). In paper III, the ImPACT equation was even further disaggregated to better reveal the actual consumption.

ImPACT has also been criticized for some of its assumptions on the proportional relationship between factors and environmental indicators (York et al. 2003). As a mathematical identity, ImPACT does not permit hypothesis testing. The value of any variable is fully determined by the values of the other variables in the identity. The ImPACT identity assumes, for instance, that a doubling of the population will lead to a doubling of the impact, all else held constant. However, the driving forces may not be independent of each other. Economic growth might enhance the development of more efficient technologies, leading to lower energy intensities. Lower energy intensities may stimulate lower carbon intensities, as outdated carbon-intensive energy plants can be closed down earlier (Duro & Padilla 2006). The dynamic interaction of the variables is not captured well in a comparative static analysis such as the ImPACT approach. Yet, this shortcoming can partly be resolved by choosing small time periods and adding further components to the equation (Feng et al. 2009). Stochastic variants of IPAT have additionally been developed, which can be used to identify the most important correlates of impact. The stochastic form enables hypothesis testing, and allows for the presence of non-linear relationships (Chertow 2000b, York et al. 2003).

In addition to variants of the IPAT identity, decomposition methodology has been developed to decompose indicator changes at the sector level since the 1970s. These are widely used in relation to trends in energy use and energy intensity. Also referred to as energy decomposition, these methods are often used to distinguish between three factors contributing to changes in aggregate energy use: changes in economic activity, structural economic changes, and changes in sectoral energy intensity (Ang & Zhang 2000, Ang 2004). Examining driving forces of CO_2 emission development at the sectoral level has also become common using various decomposition methods. There are two broad categories of these decomposition techniques (Hoekstra & Van der Bergh 2003). Index decomposition is an identity approach, and the most commonly used. The index decomposition analysis framework uses aggregate data at the sector level. Structural decomposition analysis (SDA) is an extension of conventional index decomposition (Rose & Casler 1996). SDA identifies which economic sectors and final consumers affect the change and uses disaggregated economic input–output tables. An input–output model includes indirect demand effects, i.e. demand for inputs from supplying sectors that can be attributed to the downstream sector's demand. Thus, SDA can differentiate between direct and indirect energy demands.

Compared to IPAT, the amount of data required in these sectoral decomposition analyses is large and the simplicity of IPAT is lost. In this study the ImPACT identity was used, as it allows the relationship between the driving forces and environmental impacts to be explicitly identified, and impact to be shown as a result of the interaction of the driving forces through the multiplication of factors. The IPAT identity implies that no one factor can be held singularly responsible for environmental impacts (York et al. 2003).

Due to the limited number of factors considered, some factors explaining the changes in impact or other studied indicators may be left unknown. Different decomposition methods may generate significant residuals that can be resolved by suitable decomposition techniques (Ang et al. 2003). Many decomposition methods have been developed without a residual term. The IPAT identity has been referred to as a perfect decomposition method (Zhang 2000), because it leaves no residual on the right-hand side of the equation. The change in environmental impact is entirely explained by the explanatory variables on the right-hand side of the IPAT equation. However, this is because instead of looking at real change, a logarithmic estimate of change is used.

There is a difference between the logarithmic change and the relative change in emissions, and the IPAT method is not a perfect decomposition in this sense.

Nevertheless, in taking logarithms of IPAT when the changes between examined points of time are small to medium, the sum of the percent changes in each variable closely approximates the percent change in emissions between those two years (Zhang 2000). If there are large differences between annual emissions, some perfect decomposition method can be recommended (Ang et al. 2003). When calculated for the data used and presented in this study, largest differences between logarithmic change and real change were found for nutrient emission data used in paper III. During 1980–1990, the change in the nitrogen load from Finnish aquaculture calculated with the natural logarithm was on average 18.7%/year, whereas the real change in emissions from 1980 to 1990 was on average 20.5%/year. For most data, however, the changes were found to be small (Table 3). Due to only slight differences between logarithmic and real change, the conclusions of this study remain unaffected.

When the logarithmic form is used, the sum of changes in decomposed variables equals the change in total emissions. If real changes are calculated, some slight disparities can be found between the changes in emissions and the sum of changes in drivers. This is also illustrated in Table 3. In addition, when the logarithmic form is used, time reversibility is achieved.

Table 3. Sensitivity of the ImPACT decomposition method. Annual changes in different emissions and their drivers in the 1990s in Finland are used as examples. Logarithmic change and real change in emissions, and real change in the driving forces are presented. Comparison of the log-% change relative to the actual change in emissions and comparison between the sums of changes in driving forces relative to the actual change in emissions is presented.

	NO_x (I)	CO_2 (II)	N (III)	P (III)
Time	1990-1999	1993-2004	1990-2000	1990-2000
Logarithmic change in emissions during the period (%/year)	-3.19	0.12	-4.95	-9.77
Actual change in emissions during the period (on average %/year)	-3.14	0.12	-4.82	-9.31
Sum of actual changes in the driving forces, during the period (on average %/year)	-3.07	0.23	-4.62	-9.09
Annual Logarithmic change relative to actual change	1.02	1.00	1.02	1.05
Change in the sum of actual drivers relative to change in actual emissions	0.98	1.98	0.96	0.98

5.3 System boundaries and implications of trade

The macro-level forces of one region rarely develop in isolation. Production and consumption do not often follow the same spatial borders. Related to cases of this study, there are emissions embodied in electricity and salmon imports, in traded goods in general and in international transport (Peters et al. 2009).

In paper I, the system boundaries were restricted to the geographical borders of Finland and the NO_x emissions from energy production were included. The environmental impacts of imported electricity were not included in the study. Moreover, domestic emissions of NO_x eventually spread regionally and are partly moved outside Finnish borders.

Paper II examined emissions from energy production in each of the 27 Member States of the European Union and within the EU as a whole. Electricity trade across the borders of nations was not included. In 2004 and 2005, net imports or exports of electricity in relation to country-specific total energy use were less than 10% for all EU countries (Eurostat 2009). When looking at electricity alone, the trade may be considerable for some countries. Indirect or upstream emissions, including production, conversion and transportation of fuels as well as emissions embodied in electricity production were not included in cases examining NO_x and CO_2 emissions from energy consumption and remain unveiled in this type of analysis. For instance, upstream CO_2 emissions may be around 10% of the lifecycle emissions for coal or natural gas. Moreover, equity issues related to production and consumption versus impacts due to emissions were not considered. Impacts from CO_2 emissions are global and per capita emissions in the European Union are relatively large, totalling about 9 t in 2005 (EEA 2007b, Eurostat 2007a, population data for 2004). This is approximately double the world average (Boden et al. 2009).

In an attempt to study consumption and also trade in more detail, one additional term was introduced to the ImPACT model in paper III. The system boundaries were set to include imports of salmon, as imports were separated from the technology variable. When importing Atlantic salmon to Finland, emissions are outsourced to Norway. Nevertheless, the relative contribution to eutrophication is fairly low on the coast of Norway compared to the Baltic Sea Basin.

Following the same logic as in paper III, but including the trade effects due to electricity imports, the equation would appear for energy related emissions as: population x GDP/capita x total energy consumption/GDP x domestic emissions/consumption of domestic energy x consumption of domestic energy/total energy consumption. The same holds for CO_2 and NO_x emissions. The consumption of domestic energy would omit electricity imports.

The systems perspective of industrial ecology is better realised when the system boundaries are extended to include trade. However, significant amounts of energy and energy-based emissions are embodied in traded goods. An environmentally extended input-output analysis has revealed that most countries in the EU27 are net importers of embodied CO_2 emissions (Peters & Hertwich 2008a). To include total trade effects with regards to energy, rather than using the conventional energy intensity parameter, energy embodied in trade in relation to GDP would describe the consumers of a certain country more accurately. To include such trade effects, the ImPACT equation could be modified according to the following:

$$CO_2 = \text{pop} \times \text{GDP/pop} \times \text{Energy}_{emb}\text{/GDP} \times \text{Energy/Energy}_{emb} \times CO_2\text{/Energy},$$

where ‘Energy_{emb}’ is energy embedded in consumption and ‘Energy’ simply refers to direct domestic energy use. However, reliable data on energy embodied in trade are difficult to obtain as there are high levels of uncertainty in trade statistics (Weber & Matthews 2008). In addition, there is no unique methodology to attribute energy consumption to various product systems and sectors of the economy. Moreover, the difference between production and consumption raises questions of how equity issues should be considered in sharing effort. A country with emissions embodied in exports receives the value added from relative production in any case.

5.4 MACRO-LEVEL FIGURES IN SCENARIO ANALYSIS

Macro-level figures of the economy, population, the intensity of consumption and technology are useful when exploring the trends and targets of future emissions. In evaluating the stringency of CO_2 emission reduction targets in the European Union (paper II), the analysis demonstrated the magnitude of the future challenge in relation to historical development. Kawase et al. (2006) conducted a decomposition analysis for a few EU countries with GDP scenarios until 2050, and similarly to paper II, estimated the requirement for at least a two-fold development in aggregate energy intensity and carbon intensity compared to the historical change.

Macro-level economic figures are also useful in effort sharing (paper IV). The major strength of simple top-down effort sharing methods in general is the transparency and limited amount of data required. In addition, statistics for generally known macro-level indicators are relatively well available for different countries. Forecasts of population and economic growth were considered as substantial drivers for the development of emissions. The lowering of greenhouse gas emissions per unit of economic output or per capita, as considered in the scenarios, are reasonable targets and necessary to examine in the mitigation of climate change. Some statistical sensitivities are apparent in effort sharing. However, more importantly, the choice of GDP forecasts has a major impact on the results. Even though forecasts are important when determining emissions targets, inequity is embedded in emission allowances when overestimation or underestimation of the future development of GDP occurs. The assumptions used as a basis for the internal EU effort sharing for the Kyoto period compared to the actual development as it took place were inaccurate for some of the Member States, such as Finland (Soimakallio et al. 2005).

However, when the aim is to better understand the underlying causes for the emissions development and reach greater dimensions of equity in effort sharing, a more detailed consideration of the country-specific circumstances may be required. Different types of indicators and models should be used, and their assumptions carefully considered.

5.5 Uncertainties

In general, the reliability of Finnish statistics used in papers I and III was high. Population, GDP, energy consumption and imports were based on official statistics. The older the data, the more uncertainty is likely to exist. When the data source changes, some inconsistencies may also occur. In paper I, an unrealistic abrupt increase occurred in the NO_x estimate in 1980. In paper III, the procedure for collecting fish production and nutrient load data changed in 1988. However, these changes were smoothed in the results due to use of average figures in the analysis.

Data on the population, energy consumption and CO_2 emissions for paper II were derived from the official statistics of the European Union. GDP data were from the Penn World Table, in which expenditures are denominated in a common set of prices in a common currency so that real quantitative comparisons can be made, both between countries and over time. The reliability of these official statistics is rather high.

There are, however, limitations to the reliability of the economic forecasts developed in paper II and used also in paper IV, as strong structural and dynamic assumptions are incorporated in the model. It is difficult to predict the regional or country-specific economic cycles that the EU27 will encounter in the next twelve years, or the annual real growth rates of individual countries' economies. However, a sensitivity analysis was included in paper IV, in which the implications of using different GDP forecasts, as well as different population forecasts on the emission reduction targets for internal EU effort sharing were revealed.

In paper III, some degree of deviation can be assumed in the rainbow trout production figures, fodder consumption and nutrient emissions, as the primary data were collected directly from farmers with questionnaires. Regarding fish consumption, it is difficult to know exactly what proportion of salmonids ultimately ends up in human consumption. However, if this proportion is assumed to remain unchangeable between different years, absolute consumption figures are not of great importance when changes are examined. The uncertainties were minimized by keeping data sources consistent and making comparisons between different production figures. Uncertainty analysis has been conducted for nitrogen and phosphorus flows in the rainbow trout production and domestic consumption system in Finland by Asmala and Saikku (2010) for the period 2004–2007, using methods developed by Hedbrant & Sörme (2001) and further refined by Danius (2002). However, this type of analysis was not conducted in paper III due to the smaller number of data sources needed in the paper. Furthermore, paper III was mainly based on reliable official national statistics, whereas in Asmala and Saikku (2010) more uncertain data sources were also used.

In general, systematic quantitative uncertainty analyses are not common in studies using the ImPACT method and have been little developed. However, Ausubel & Waggoner (2008) explored the differences in the intensity of energy use and CO_2 intensities of energy due to the use of varying data sources. According to the authors, the differing rates of change implied by different agencies and methods used for providing the energy and CO_2 data highlight the caution required in interpreting the results. In addition, Marland et al. (2009) have discussed the uncertainties in CO_2 estimates in general. However, analysis of the reliability of official national statistics was beyond the scope of this study.

5.6 Reducing emissions

In the industrial ecology view, using technology to reduce environmental impacts could, in theory, reduce environmental impacts for more people overall and more affluent people in particular (Chertow 2000b). The sustainability challenge approach, defined by Waggoner & Ausubel (2002), refers to compensating the environmental impact of the growth in population and affluence by lowering the intensity of use (C) and technology variables (T). With regards to this study, the emission intensity of energy production could be improved for NO_x by lowering the nutrient content of fuels, or by cleaning exhaust gases. Carbon capture and storage (CCS) is an option for CO_2, yet currently not economically feasible. Changes in the mix of fuels, reorganization of the structure of energy production and technological innovations are crucial to lowering the emissions of both CO_2 and NO_x. Regarding the intensity of energy use, making combustion more efficient by technical means alone is insufficient due to rebound effects (Hanley et al. 2009).

As regards the sustainability challenge and a further reduction in nutrient emissions to the Baltic Sea (paper III), changes would be required in consumption, technology and in the share of domestic production of total consumption. Regarding technology, limits to the biological and physical properties of cultured fish species, among other factors, are faced at a certain point. Regarding consumption, salmonids are preferred to many other protein sources, and high income elasticities observed in the recent past also indicate continuing growth in relation to affluence. Regarding trade, increasing imports of salmonids will outsource the impacts.

The approach used here implies that besides improving the intensity of use and technology variables, entirely new viewpoints and options may be needed for emissions reduction. Besides reducing CO_2 emissions due to energy consumption, climate change mitigation also has to focus on other greenhouse gases, on albedo changes and on aerosols. Also the potential role of biomass as a carbon sink (paper II, Peters et al. 2009, Canadell & Raupach 2008) must be recognised. At other sectors than energy, such as agriculture, forestry and waste management cost-efficient options may also exist (Delhotal et al. 2006). The implementation of emission reductions in developing countries instead of reducing intensities in the developed countries is often cost-effective. Also, there are potentially vast indirect benefits of GHG emission reduction policies in developing countries that create stronger incentives for the countries to participate in international climate change policies (Halsnäs & Olhoff 2005). Achieving an international binding agreement on emission reduction targets and measures is necessary to avoid potential leakages and rebound-effects.

Reducing the total amount of nutrients cycling in energy systems and eventually contributing to NO_X emissions should be emphasized (paper I). Considering aquaculture emissions, closing of the nutrient cycles follows the principles of industrial ecology. Nearly all of the ingredients used in rainbow trout feed originate from outside the Baltic Sea basin. Thus, even the most efficient use of feed results in the accumulation of nutrients in the Baltic Sea. Aquaculture production requires up to 5 kg of fish in feed to produce 1 kg salmonids (Tacon & Basurco 1997). The eutrophication problem could be dealt with by replacing imported fish in feed with fish originating from the waters surrounding the production site (Asmala & Saikku 2010).

The world population is projected to grow to over 9 billion by 2050 (Population Reference Bureau 2009). Even the trend of a declining population in highly developed countries could be reversed as a result of continued economic and social development (Myrskylä et al. 2009). With higher population levels, economies might have to resort to lower quality energy resources according to Holdren (1991). The increase in energy or electricity demand will, in the short term, be met with the energy sources in the production margin, often the most emission-intensive ones (Soimakallio et al. 2010). New investments are determined by the developments in energy prices, energy consumption and climate policy, among other factors. Installations of new production capacity, such as clean technologies, to supply the increased consumption due to population growth may reduce the availability of such capacity for later increases in energy consumption.

The environmental impact of population growth will be reinforced by other demographic trends. The trend of rising urbanization is widely acknowledged. The average household size in developing countries is also likely to fall as young people move away earlier from their family home, marry at a later age and their parents increasingly live in separate homes (Cole & Neumayer 2004). The development of an aged society can be expected to increase residential energy demand due, for instance, to smaller household sizes, spacious housing, free-time-rich lifestyles and accumulated consumer durable stock (Yamasaki & Tominaga 1997).

The sustainability challenge approach applied in scenario analysis in paper II clearly showed that reducing energy intensity and improving technology in the European Union in order to mitigate climate change in the near future is a huge challenge. Globally, in a world of 9 billion people, assuming 2% annual economic growth, global carbon intensity would need to fall, on average, by more than 11% per year and to be almost 130 times lower than they are today to stabilize the GHG concentrations in the atmosphere by 2050 (Jackson 2009). Schor (2005) has also argued that increased energy efficiency and efficient technologies are likely to develop in the future, although not sufficiently. Schor (2005) states that 1) shifting to environmentally sound technologies will require a much higher pace than in the recent past; 2) any consumption, even clean, requires some extraction and transformation of natural resources; 3) rebound-effects exist; and 4) the life-styles of developed countries will spread world-wide.

Attaining economic growth in terms of GDP can be questioned, and measures relating more to well-being than general market activity could instead be considered (Stiglitz et al. 2009, Jackson 2009). Means to restrain growth in terms of GDP, for example through working hour reductions, or supporting labour-intensive services, have been discussed by Schor (2005) and Jackson (2009), among others. Decomposing affluence A (GDP/capita) to GDP/welfare x welfare/population, in the existence of proper data,[8] would reformulate the ImPACT equation. This would emphasise the role of aiming at increasing welfare per person instead of increasing GDP.

Besides GDP, constant population growth in relation to environmental problems has recently been discussed. One cost-benefit analysis concluded that when considered purely as a method of reducing future CO_2 emissions, family planning is more cost-effective than most low-carbon technologies, and the study recommended that family planning should be seen as one of the primary methods of emissions reduction (Wire 2009). Murtaugh and Schlax (2009) state that family planning should be given much more emphasis when discussing the total carbon emissions of individuals. Population and affluence issues might be worth taking into account in decision making over long-term climate policies, and further research on these subjects is certainly needed.

Climate policy has impacted on environmental emissions only in the recent past. The easiest ways to reduce emissions are often cost-effective, and the low-hanging fruits may already have been picked in some countries. However, many cost-saving measures exist that need to be enforced by policies. Even though currently costly, climate change mitigation will eventually appear less costly than potential climate change adaptation if climate stabilization targets are not met (Stern et al. 2006).

[8] Such as overall life satisfaction index from World Values Survey database, available at www.worldvaluessurvey.org

Environmental policies in general must cover all the regions related to production and impact in order to avoid leakage effects, as demonstrated in paper III.

5.7 Further research

The potential and costs of achieving the sustainability challenge related to various environmental emissions with technology and dematerialisation must be further studied. Respectively, the role of two other drivers present in ImPACT identity, population and affluence, in achieving ambitious environmental goals requires careful attention in research. For instance, aiming for happiness and using welfare indexes instead of GDP as a measurement for growth might be considered overall, and in particular in ImPACT analyses like those conducted here.

Outsourcing the impacts due to trade is not a globally sustainable solution. The role of international trade is an important issue when addressing environmental problems and needs further exploration (Peters et al. 2009). International trade could be included in ImPACT analyses by including exports and imports as in paper III, or by including estimates of embedded emissions or embedded energy in trade. Currently, there is considerable uncertainty in consumption-based emission estimates. Moreover, when considering CO_2 emissions, the role of land-used changes, including agriculture and forestry, and vegetation sink arises (Rautianen et al. 2010). The sinks also embodied in trade are not well known. In effort sharing, the role of consumption and of emissions embodied in trade, as well as equity issues, deserve more attention. The use of macro-level figures for effort sharing could also be applied to other environmental emissions besides GHGs (paper IV), such as in the mitigation of the nutrient load to the Baltic Sea. GDP, population and country-specific nutrient emissions could serve as a basis for calculating country-specific emission reduction targets.

6 CONCLUSIONS

A key concept in the field of industrial ecology, ImPACT decomposition analysis, explores key drivers behind emission change. ImPACT identity was here successfully applied and developed in diverse case studies. Examples cover long historical time series, local environmental issues with regional implications including international trade, and scenario analysis.

Examining long historical time series since the 1950s showed that Finnish energy-related NO_x emissions started to decrease in the early 1990s as technology improved and the intensity of energy consumption decreased (paper I).

Carbon dioxide emissions in the European Union region during the studied period 1993–2004 increased (paper II). The emission intensity of energy and the economic intensity of use did not improve enough to offset the growing affluence. Scenario analysis further implies that the challenge in improving technology and the intensity of consumption in relation to CO_2 emissions in order to meet even short-term moderate climate targets is enormous.

The nutrient load from Finnish salmonid consumption was studied in paper III. Nutrient load started to decrease in the 1990s, even though affluence and the intensity of consumption strongly increased. However, technology improved strongly reducing the nutrient load to the Baltic Sea. Also, an additional variable included in the analysis, imports of salmon, was a driver for decreasing domestic emissions.

When analyzing historical changes in emissions and underlying drivers, ImPACT decomposition analysis is a useful tool. In addition, macro-level figures are helpful in estimating the stringency of environmental targets in relation to historical development and in setting up country-specific environmental goals. The rates of projected population and affluence growth are especially worth consideration in setting targets. The advantages of such simple and widely used approaches are the transparency, good availability of data and reliability, thus improving general understanding. However, sensitivities in calculations must be carefully acknowledged.

However, in a globalised world, production, consumption and related environmental impacts are more and more spatially and temporally separated. This type of analysis is best suited to the global scale. Nevertheless, trade and consumption could be treated explicitly in the country-specific historical decomposition analyses as presented in paper III, or at least they should be discussed in depth in similar analyses.

Growth in affluence is a powerful driver for emissions growth. Increasing population steadily scales up the impact. According to the sustainability challenge approach, the environmental impact of the growth in population and affluence should be compensated by improvement in the intensity of use and technology. Time is running short, at least considering the achievement of ambitious climate change mitigation target. It is not certain whether the sustainability challenge can be met. Most likely, the aim for ever-increasing affluence, implying increasing consumption and the promotion of current western life-styles, will need to be critically discussed. In addition, the role of population growth in relation to environmental problems and their solutions must be considered. The role of environmental policy at local and global levels is important in order to achieve the ambitious emission reduction targets and avoid leakages and outsourcing of emissions.

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